Studying cosmic rays with the Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

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Outline

Ultra-high energy cosmic rays

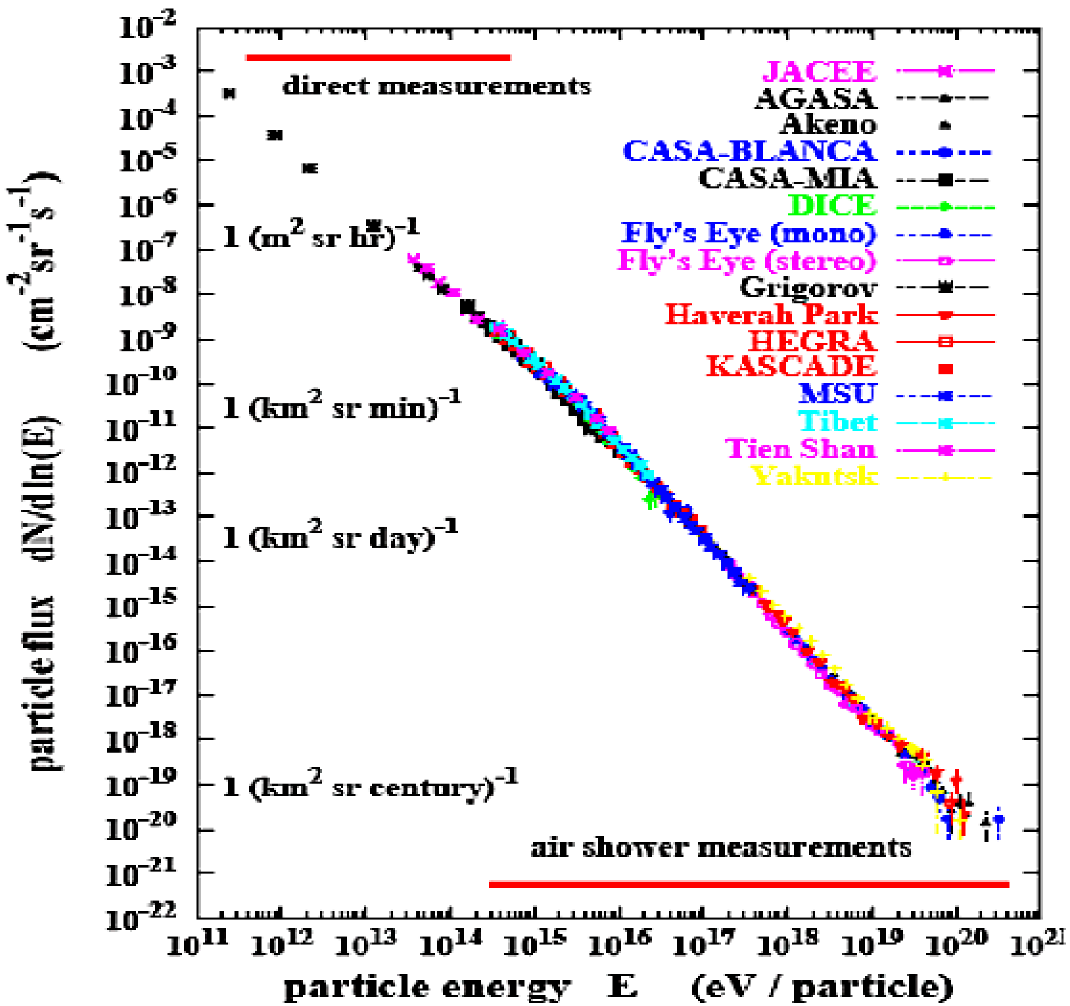
Experimental procedures

Scientific results

- Energy spectrum
- Arrival directions
- Composition
- Hadronic interactions

Cosmic rays

Cosmic ray energy spectrum



Ultra-high energy cosmic rays

Origin of ultra-high energy cosmic rays($E > 1$ EeV = 10^{18} eV) remains unclear

Acceleration in known astrophysical objects (bottom-up)?

- radio galaxies, AGN,...
  - large Z nuclei easier to accelerate $E_{max} \propto Z\,B\,L$
  - neutral particles only secondary

Exotic processes (top-down)?

- topological defects, relic particles,...
  - photon/neutrino dominance
  - no heavy nuclei

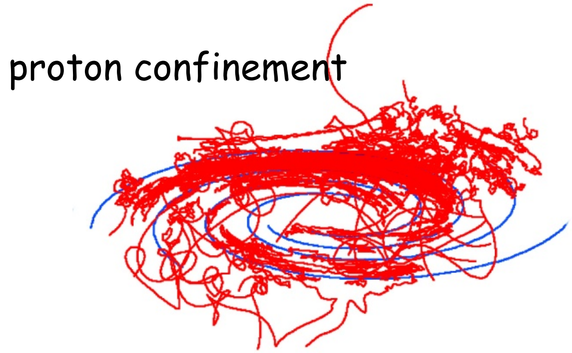
Hybrid scenarios, e.g. new properties of known particles?

- new particles, Lorentz invariance violation,...

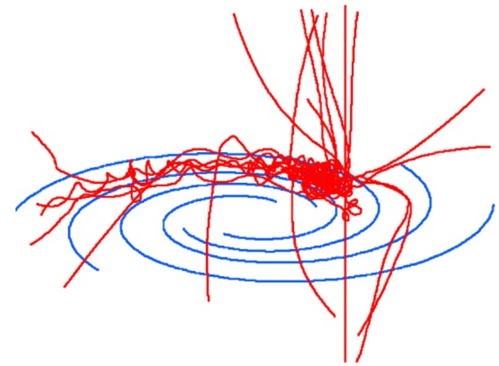
Need measurements of

- arrival directions
- energy spectrum
- composition

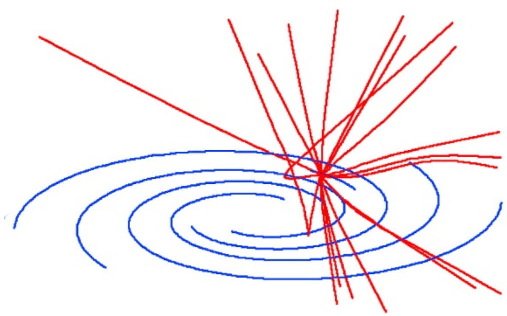
Cosmic ray propagation in the Galaxy



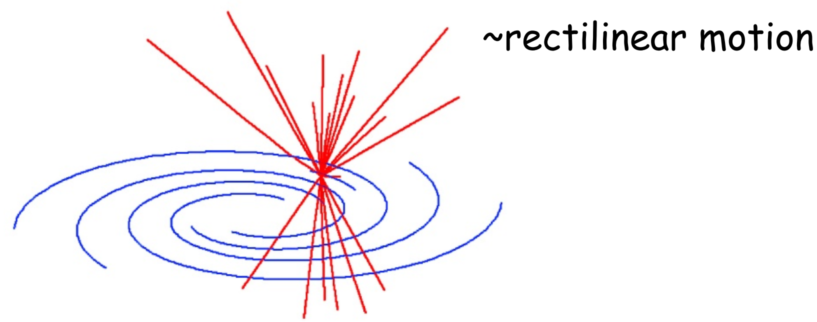
$10^{17} eV$



$10^{18} eV$



$10^{19} eV$



$10^{20} eV$

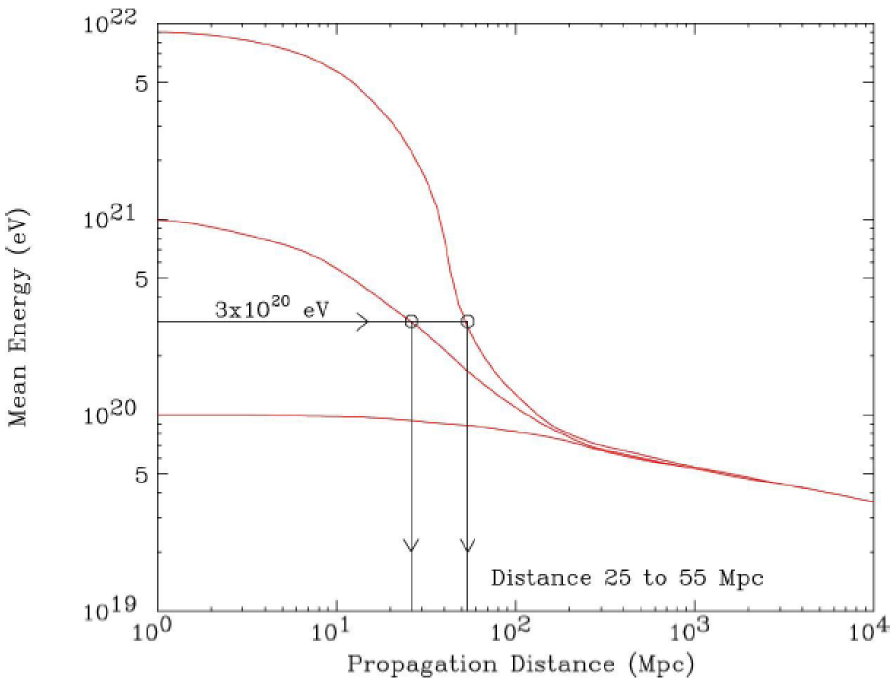
GZK effect

Greisen-Zatsepin-Kuzmin effect
interactions with CMB photons
at E > ~5×10^{19} eV:

$$p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0$$
$$\qquad\qquad\qquad n + \pi^+$$

→ reduction of proton energy
→ spectrum steepening

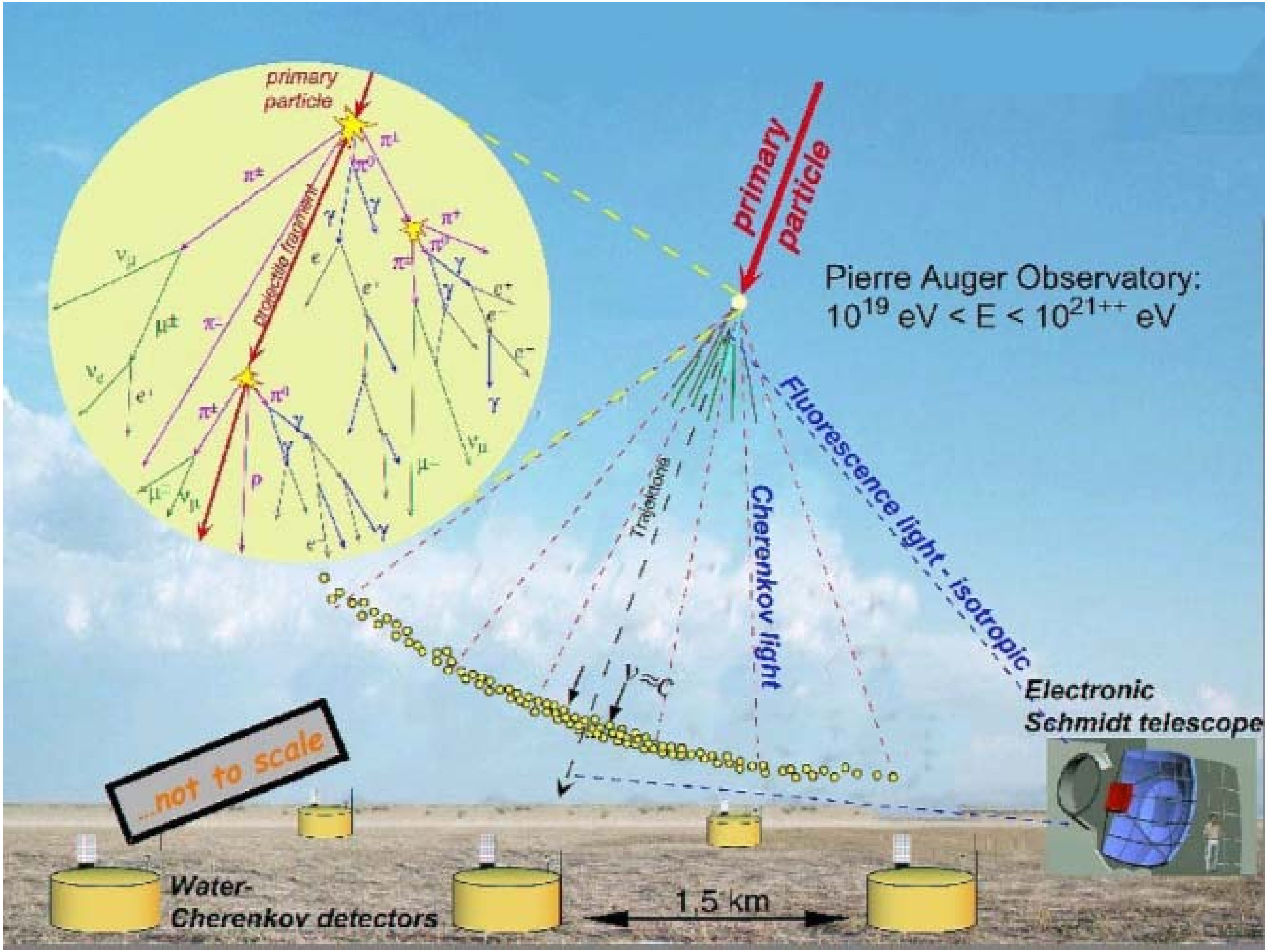
For E > 10^{20} eV the source must be within ~ 50 Mpc
source identification should be easy??



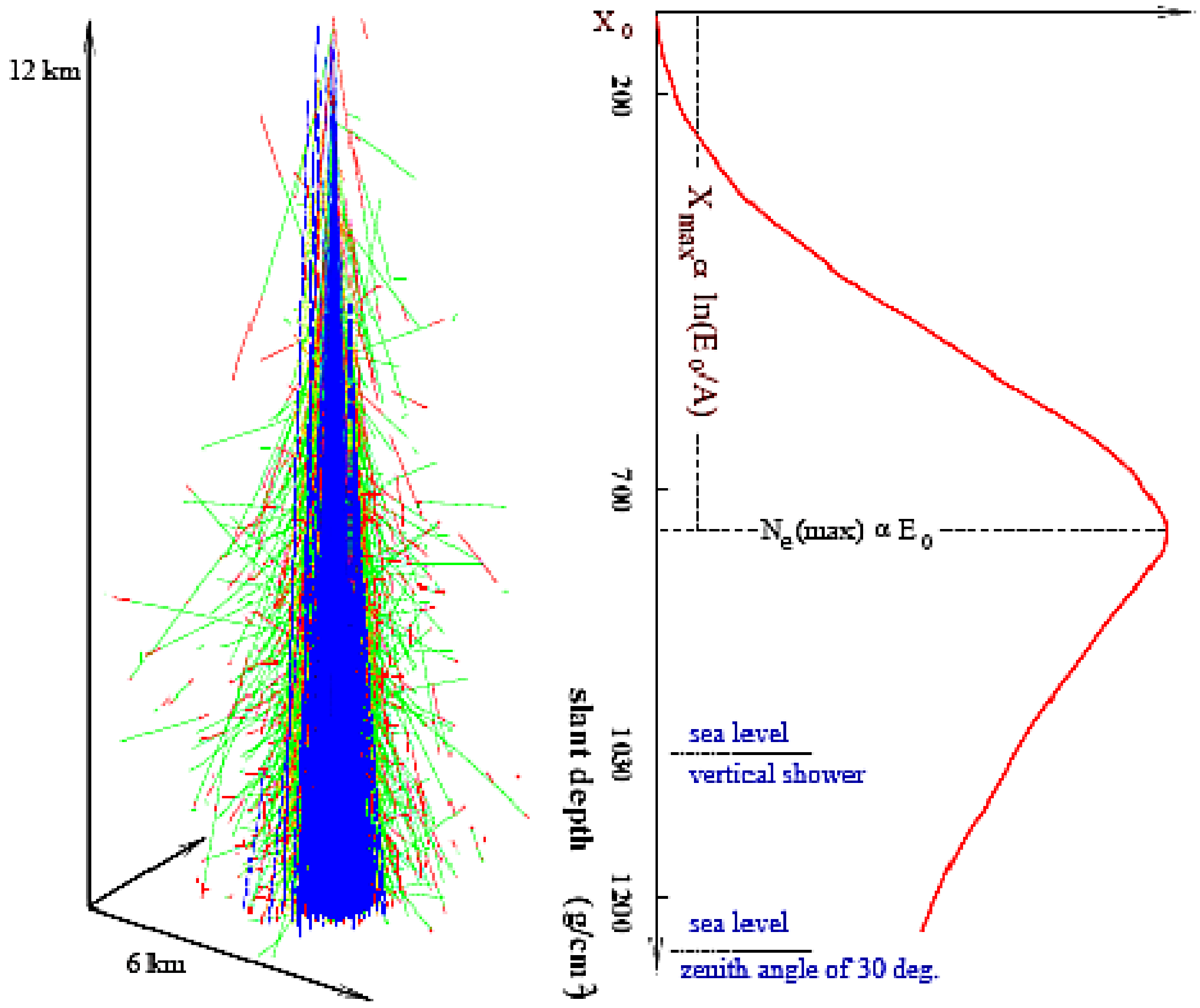
Charged particle astronomy should be possible

The experiment

Extensive air shower

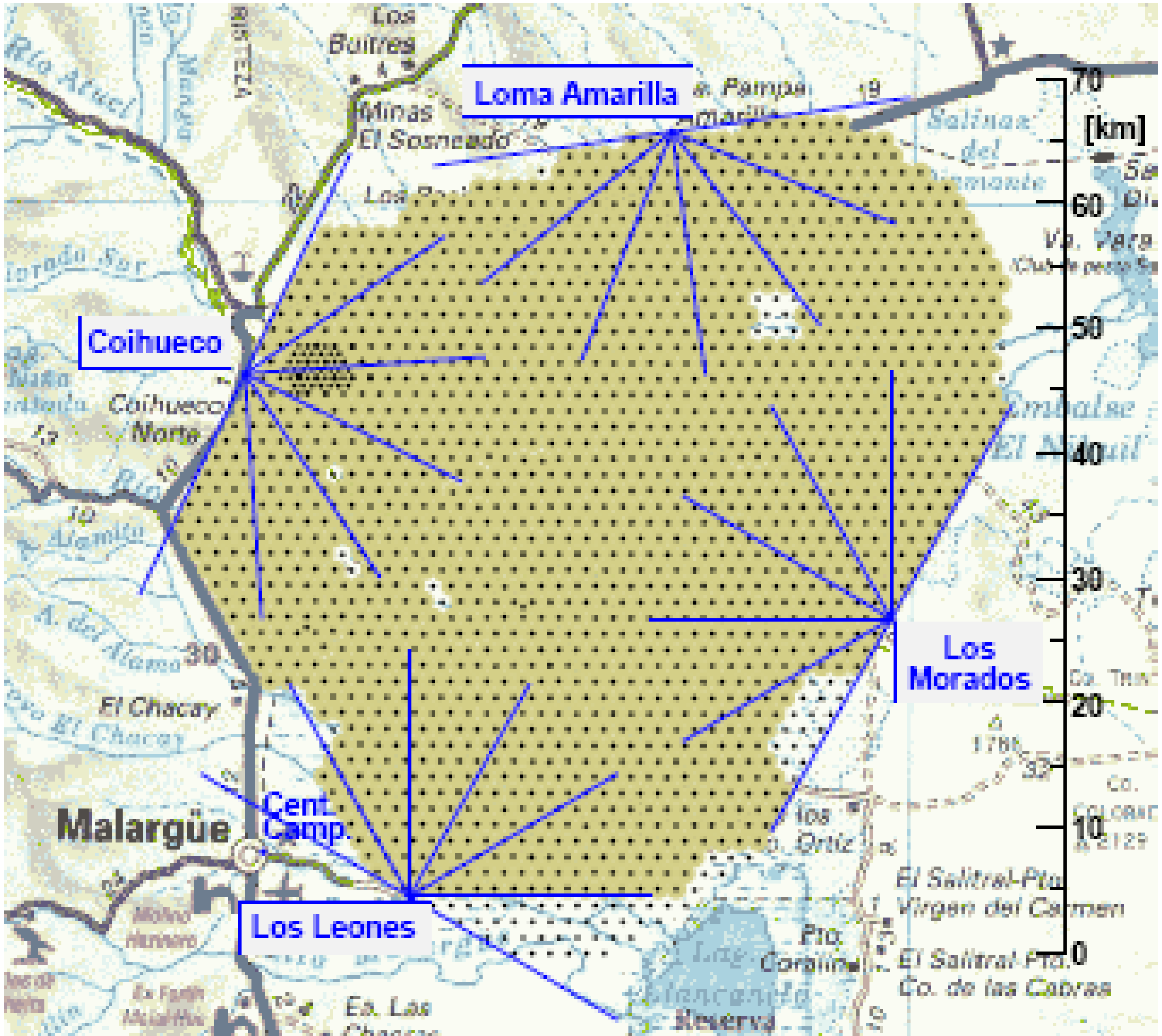


Air shower development



The Pierre Auger Observatory

Located in Mendoza province, Argentina



Surface Detector

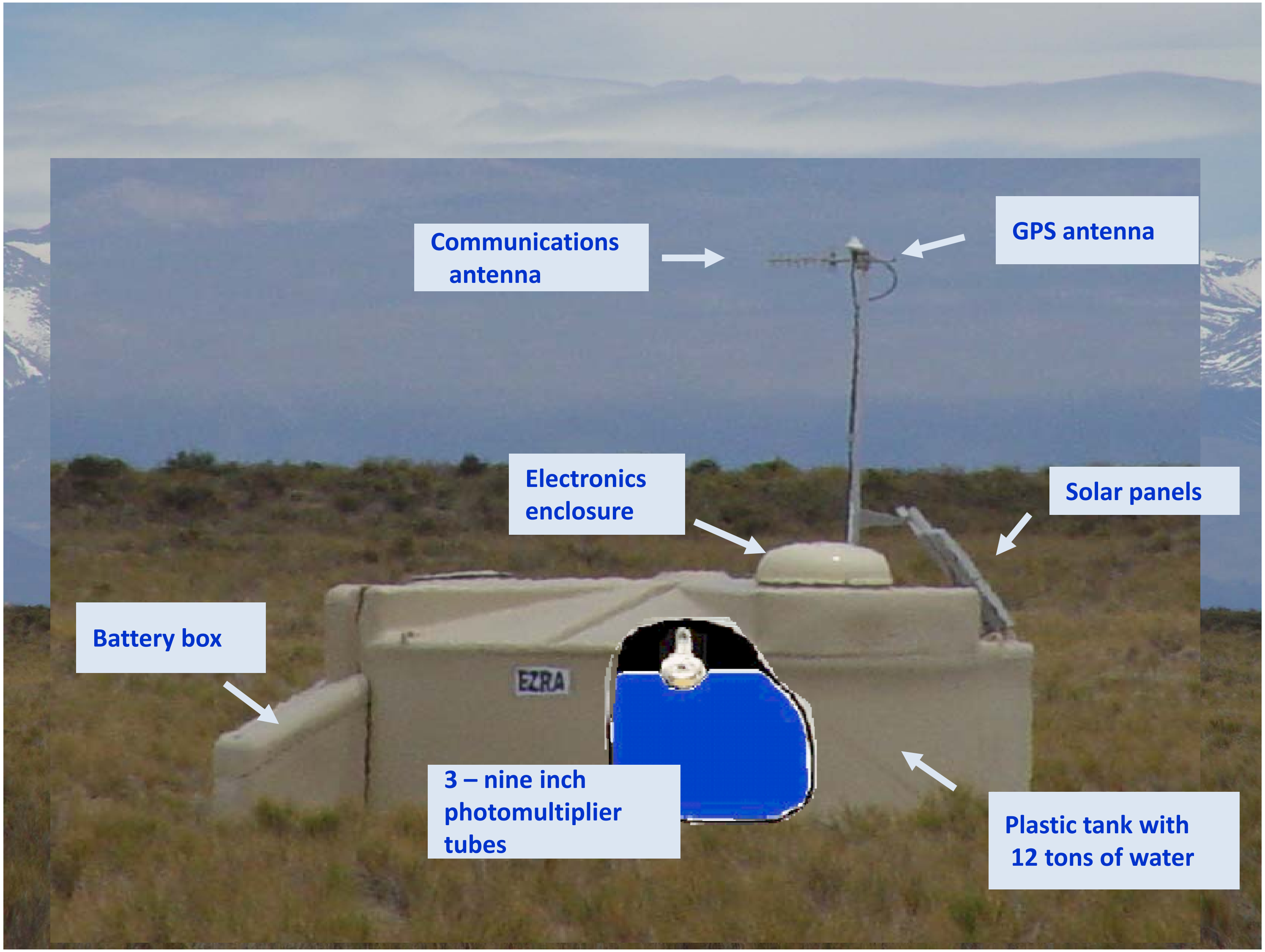
1600 detector stations
1.5 km spacing
3000 km^2
100% duty cycle
exposure calculated geometrically

Fluorescence Detector

24 telescopes
calorimetric energy
duty cycle ~13%
exposure based on MC

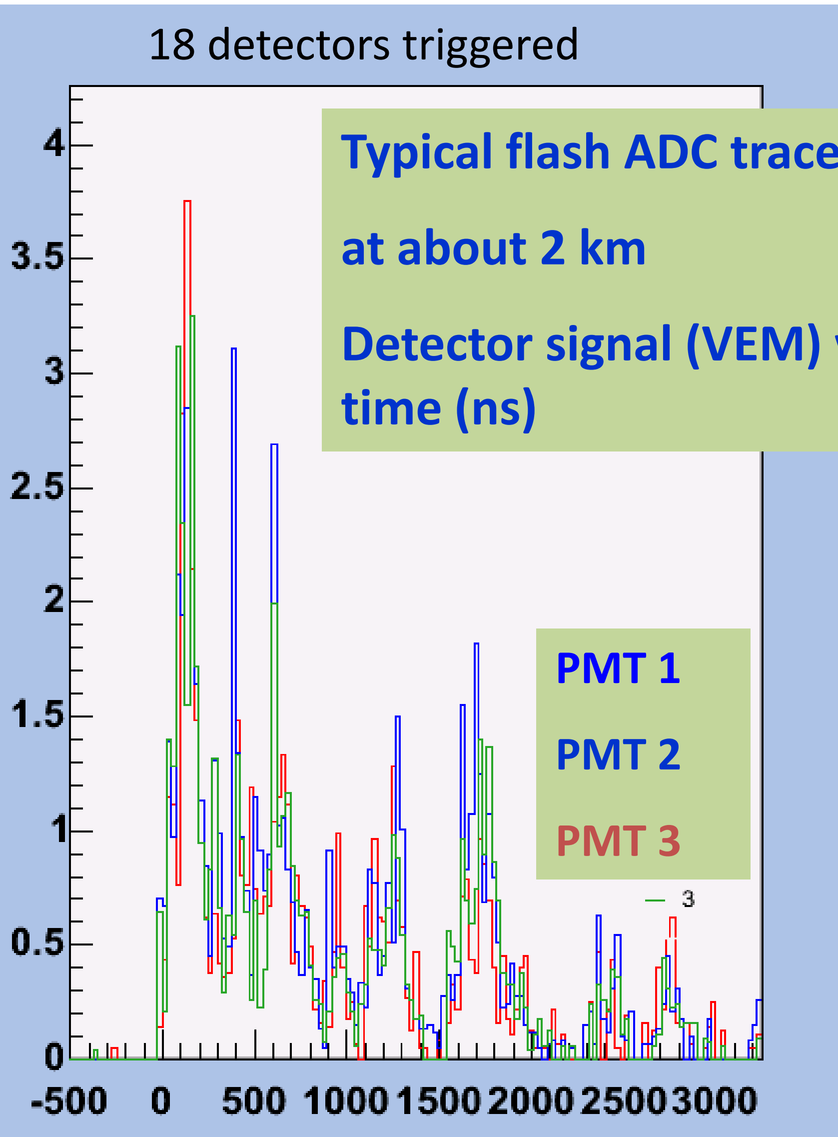
Surface Detector Station

Surface Detector Station



SD shower reconstruction

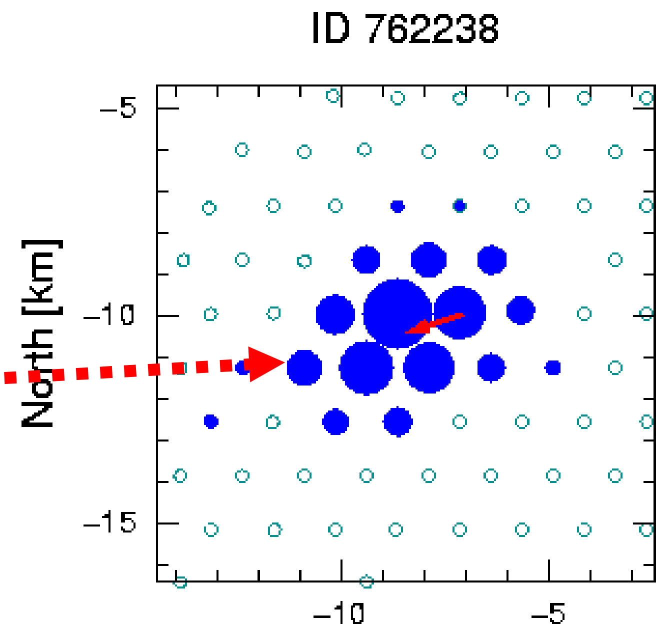
θ~ 48°, ~ 70 EeV

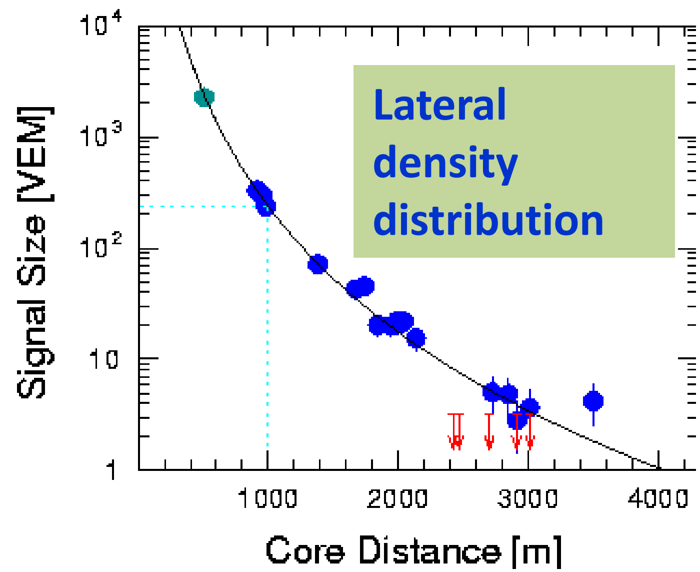


Typical flash ADC trace

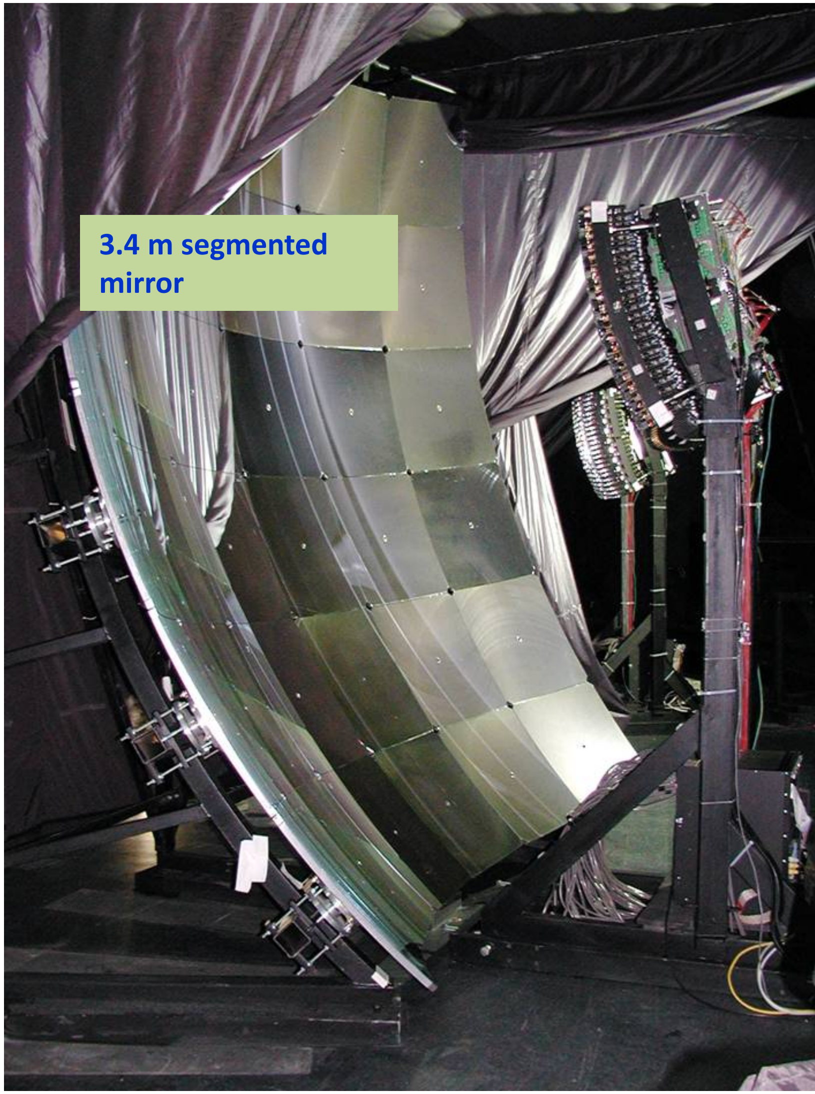
at about 2 km

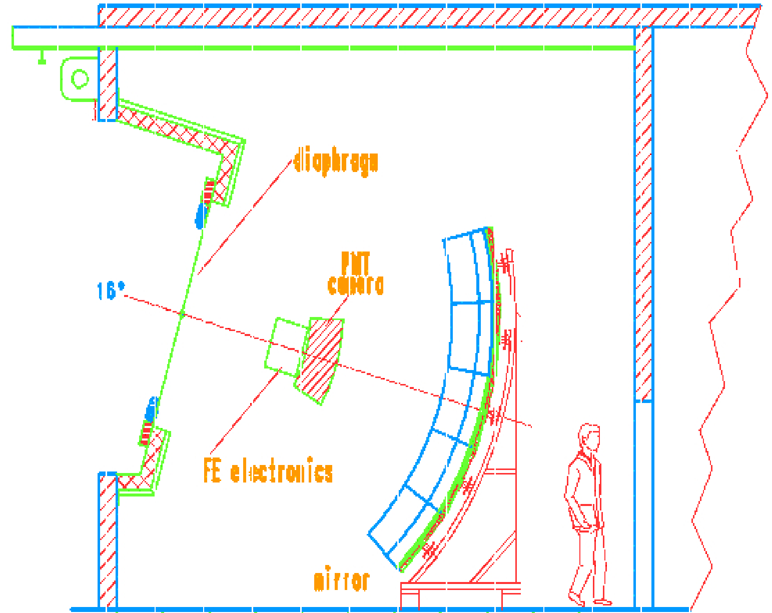
Detector signal (VEM) vs time (ns)

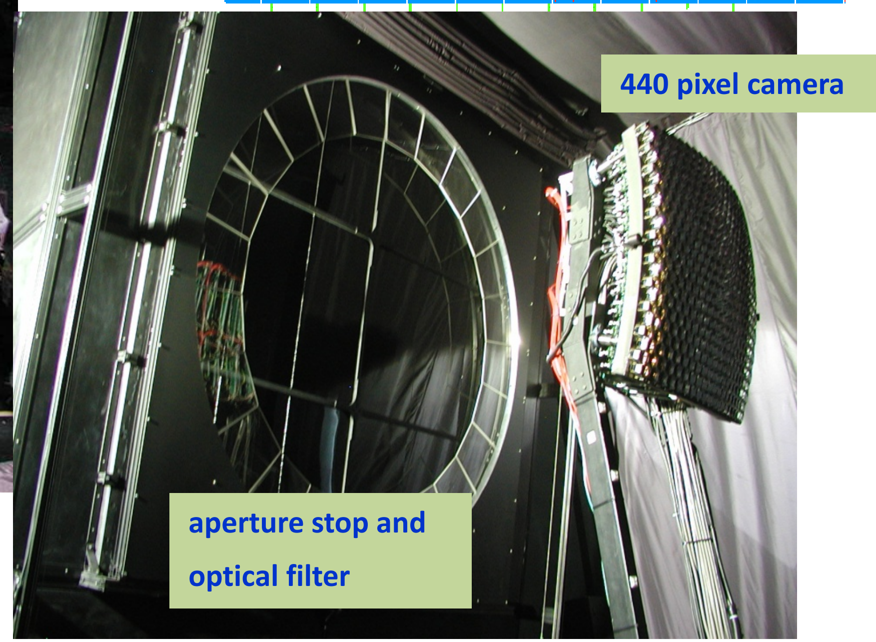




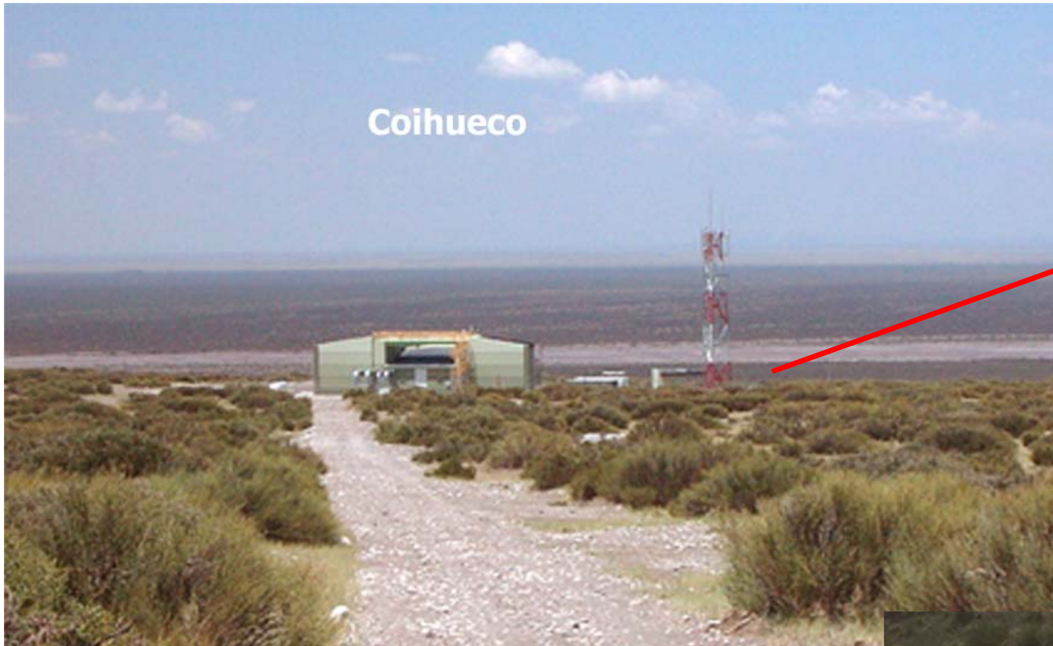
Fluorescence detector

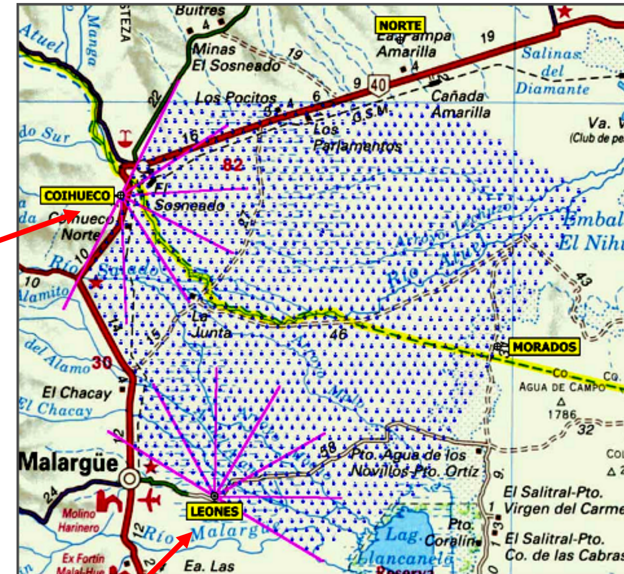


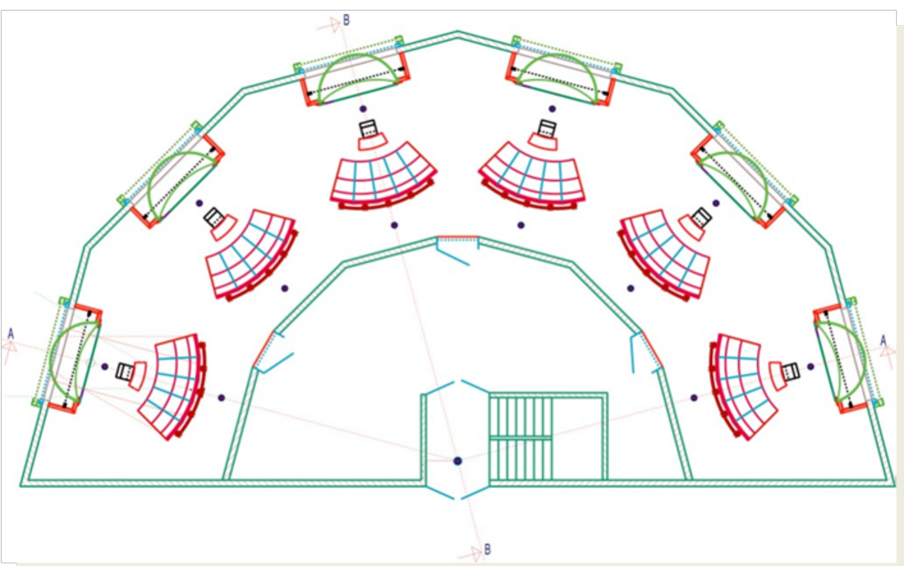


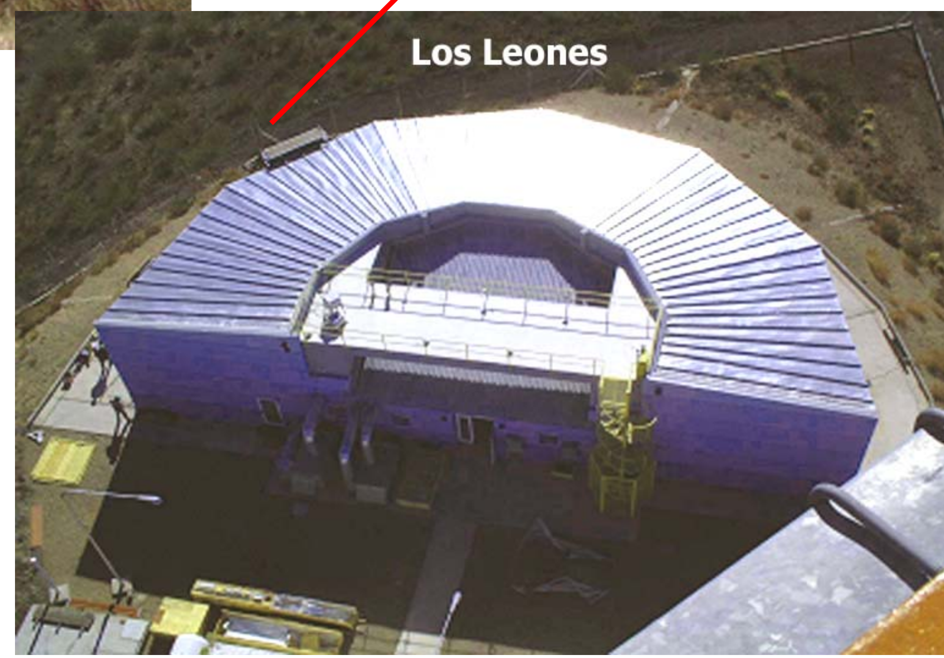


Fluorescence detector „eyes"



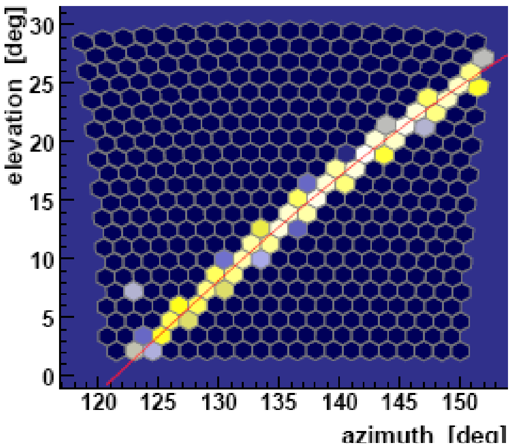


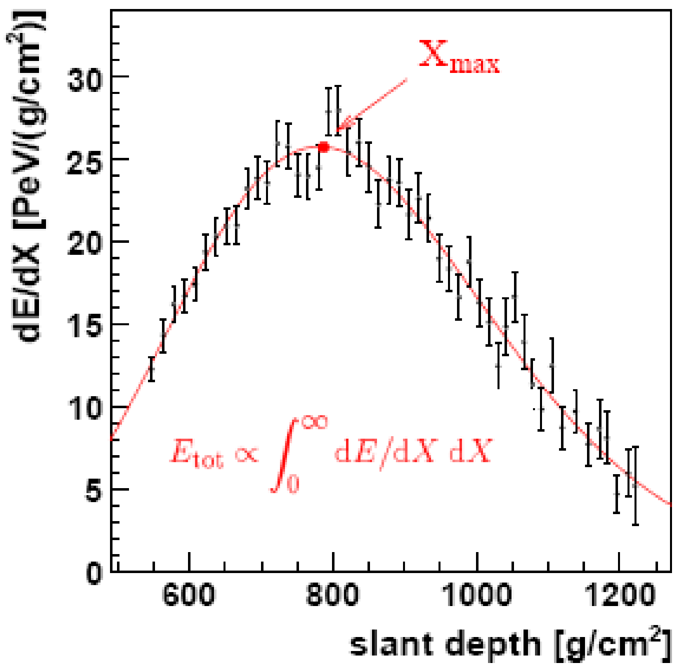


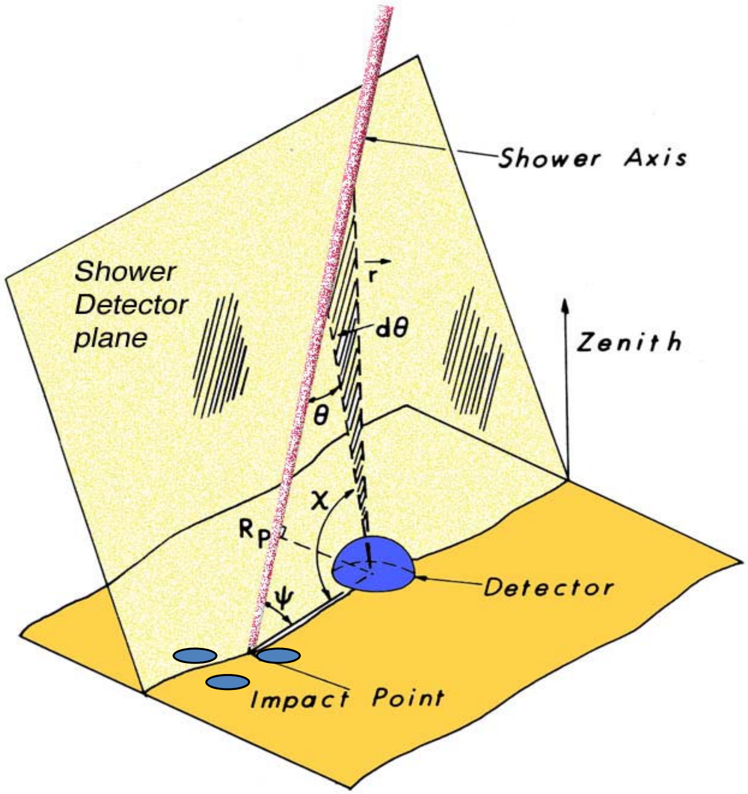


FD reconstruction

camera view

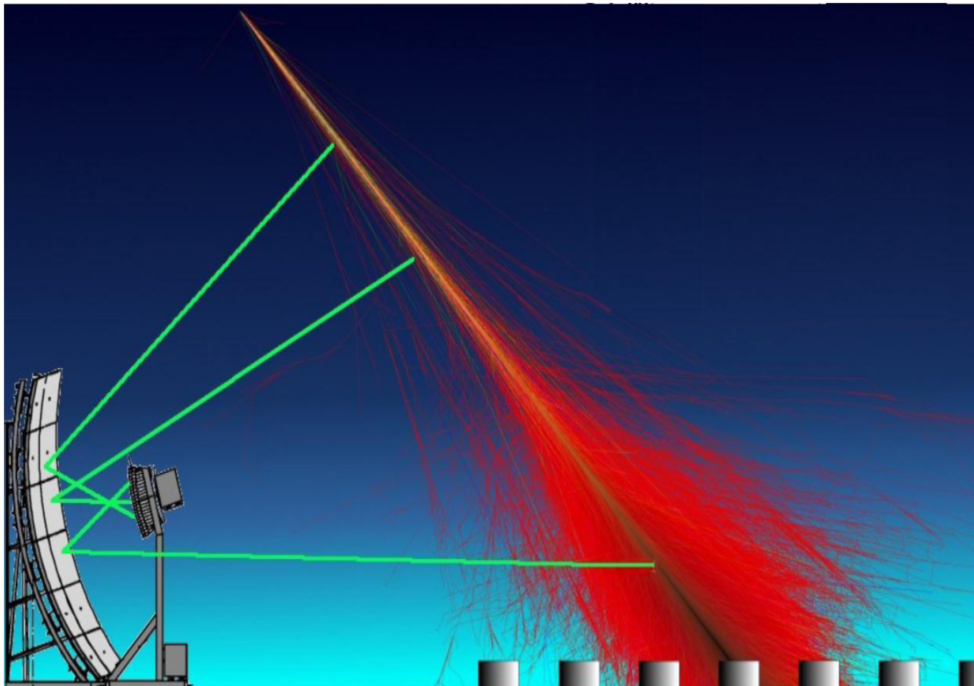






Precise shower geometry using SD signal timing

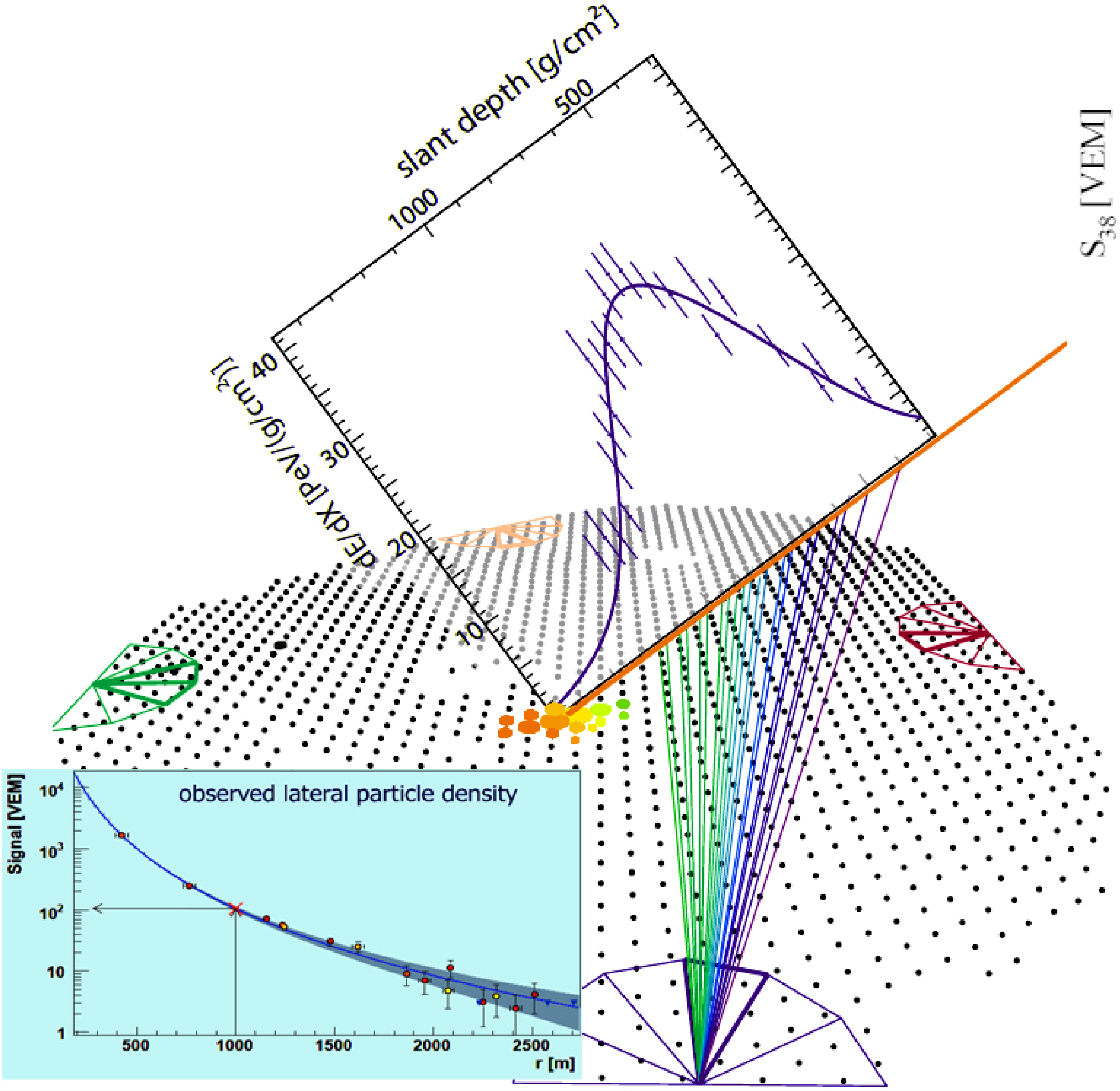
enables high precision of energy and X_{max} reconstruction

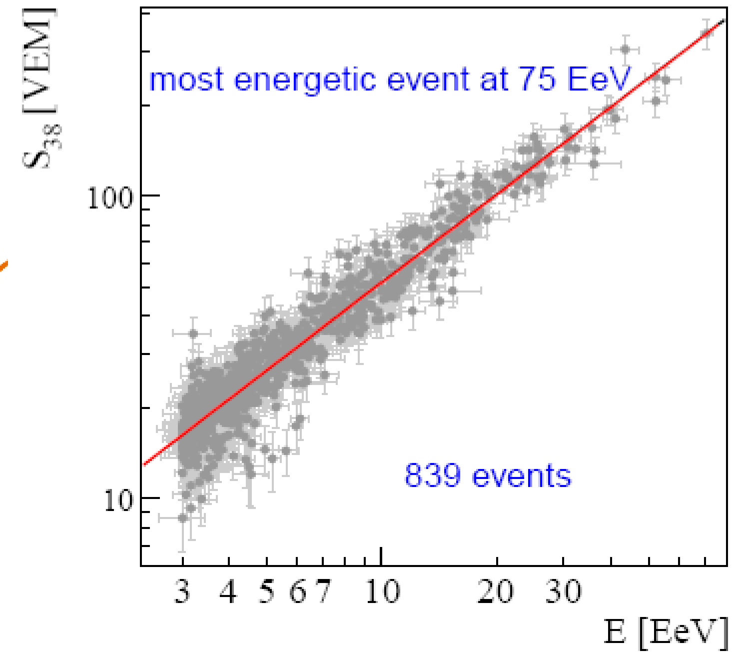


Hybrid detection of extensive air showers

Use simultaneously both FD and SD techniques

Hybrid reconstruction

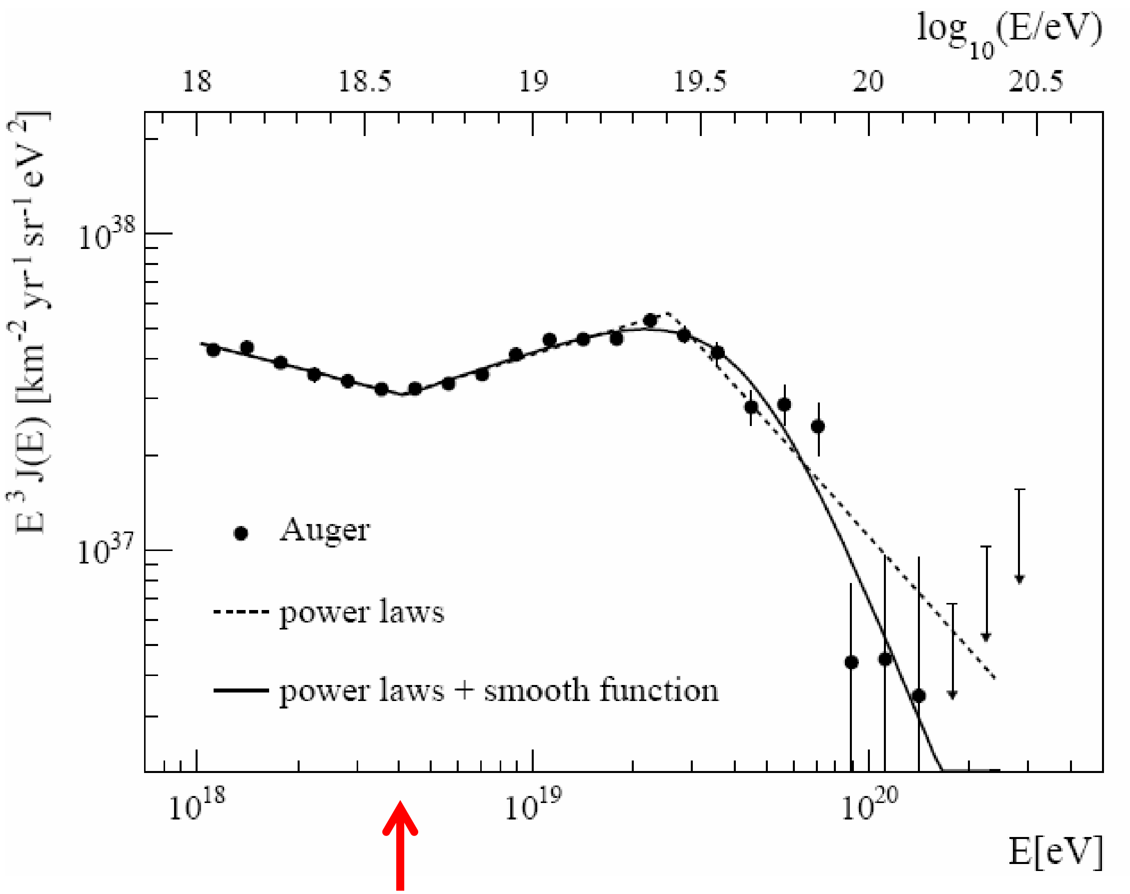




FD-SD energy calibration

Energy spectrum

Energy spectrum



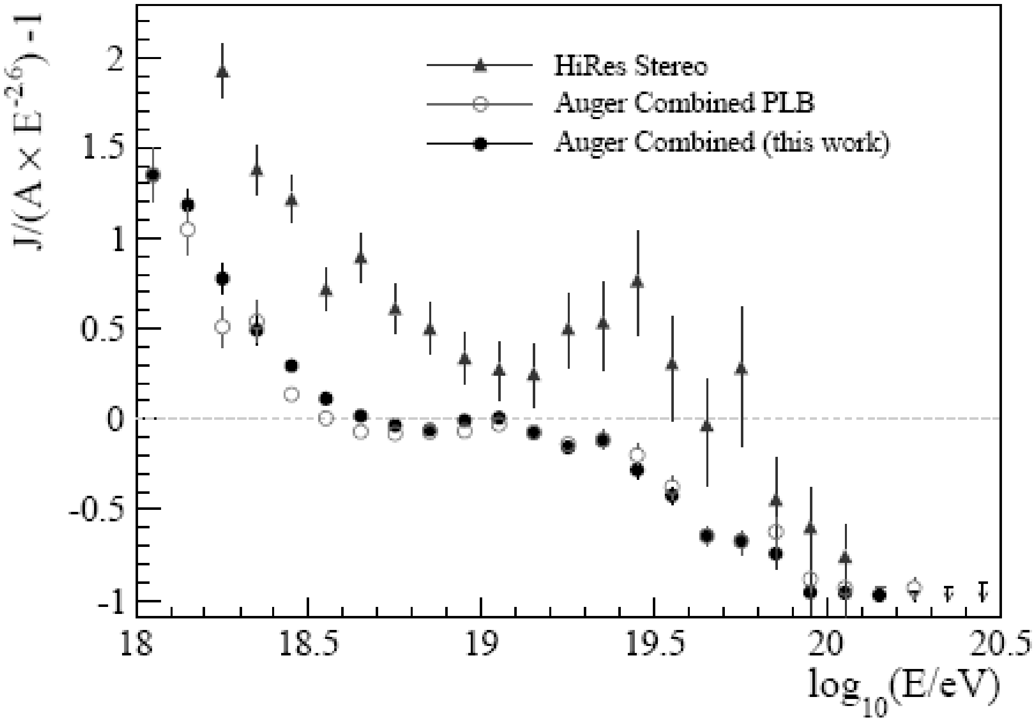
Break in the spectrum (significance >20 σ) consistent with the GZK cutoff,

but other explanations (e.g. maximum energy of accelerator) not ruled out yet

Composition measurement is crucial

E_{ankle} ~ 4 EeV (gal. $\rightarrow$ Xgal?)

Auger and HiRes spectra



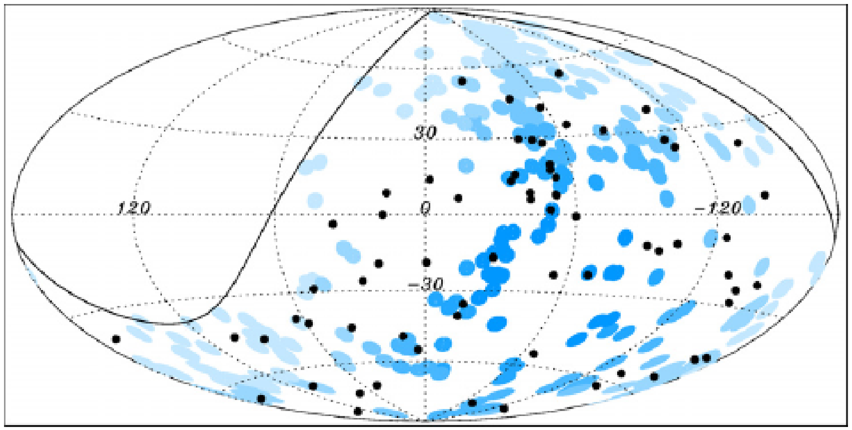
Spectra consistent within experimental uncertainties

Systematic uncertainty on energy scale 22% (dominated by fl. yield 14%)

Arrival directions

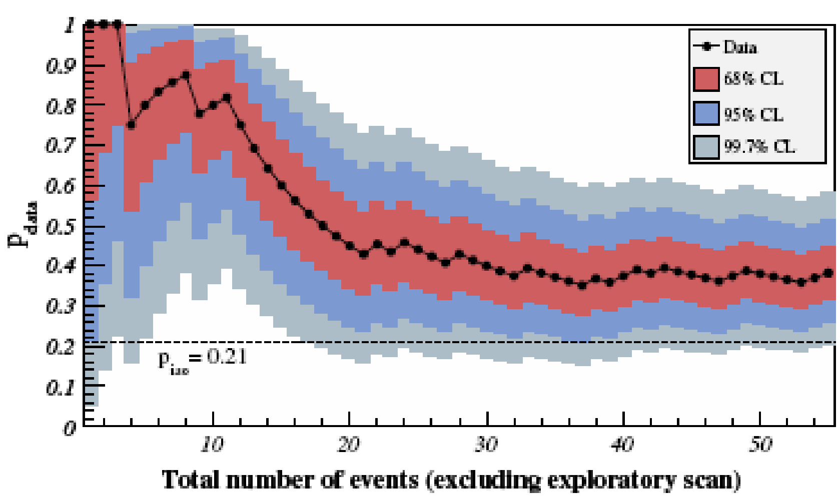
Cosmic ray sky map

Correlation with Veron-Cetty Veron catalog



Arrival directions of cosmic rays of energy >55 EeV (black points) and locations of VCV objects that lie within 75 Mpc
(blue circles of radius 3.1° – color intensity proportional to exposure)

Angular scale suggests proton primaries

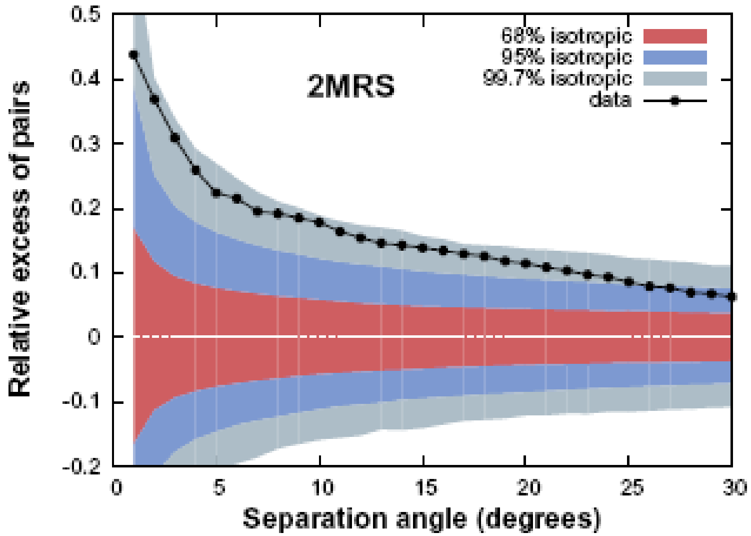


69 events (55 excluding exploratory scan) E > 55 EeV, anisotropy 99% C.L.
38% of cosmic rays correlate with AGNs from VCV catalog

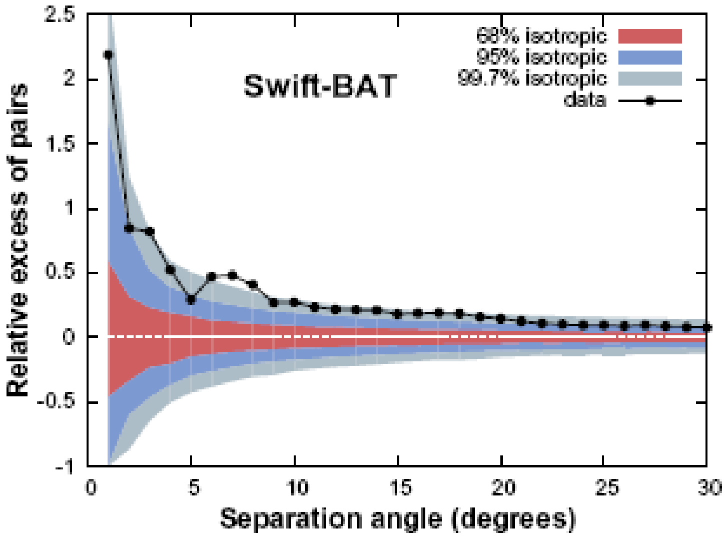
Other catalogs

Correlation between arrival directions of E>55EeV cosmic rays with positions of galaxies that lie within 200 Mpc

Angular distance from cosmic ray direction to the nearest object in catalog

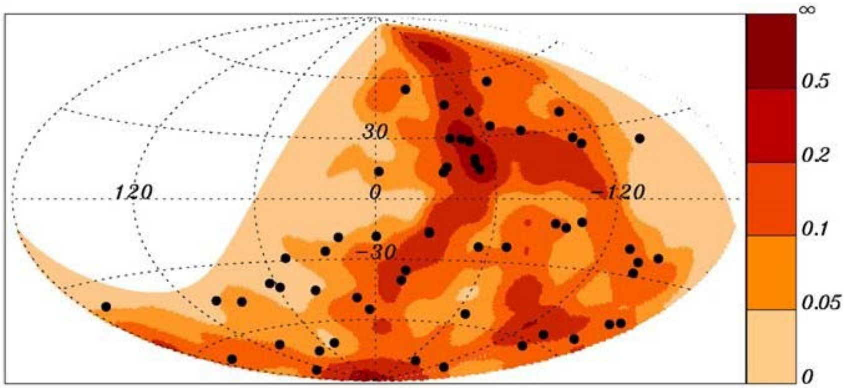


57 events b>10 deg

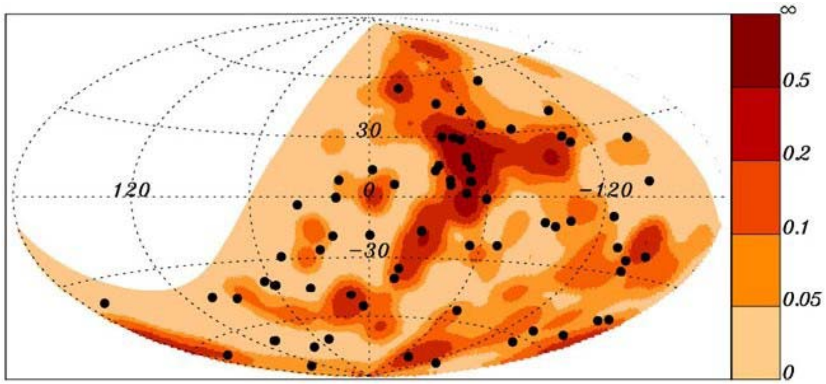


69 events

Other catalogs

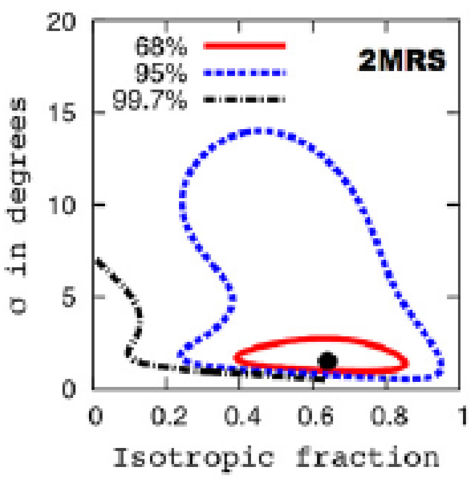


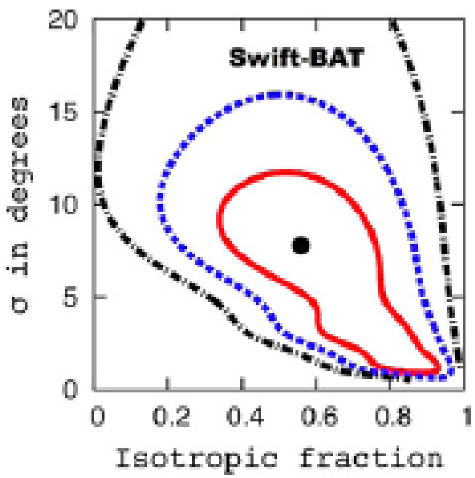
2MRS



Swift-BAT

Find best values of smoothing angle and isotropic fraction to fit experimental distribution to distribution of galaxies

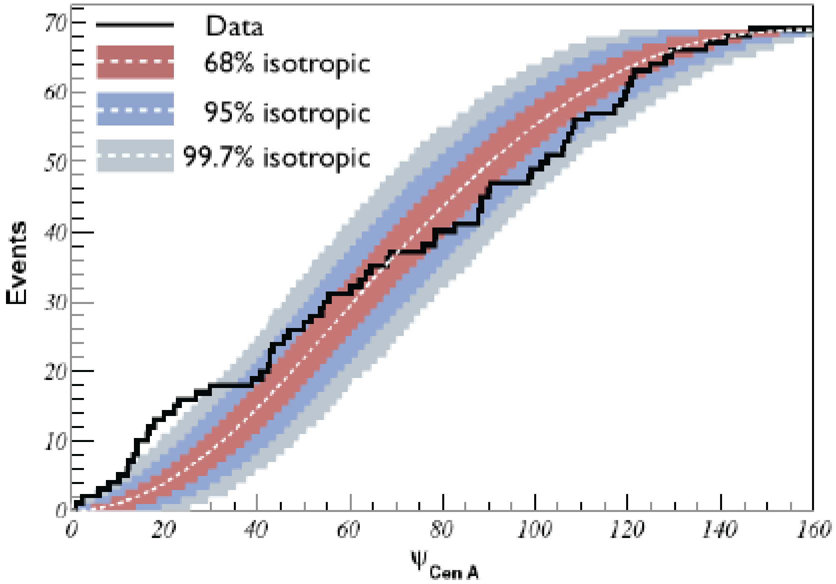




A large fraction (~60%) of cosmic rays is required to be isotropic to obtain best match

Centaurus A

Cen A: the brightest radio source of the sky (d ~3.5 Mpc)



Correlation of cosmic ray directions with Cen A

13 events within radius of 18°

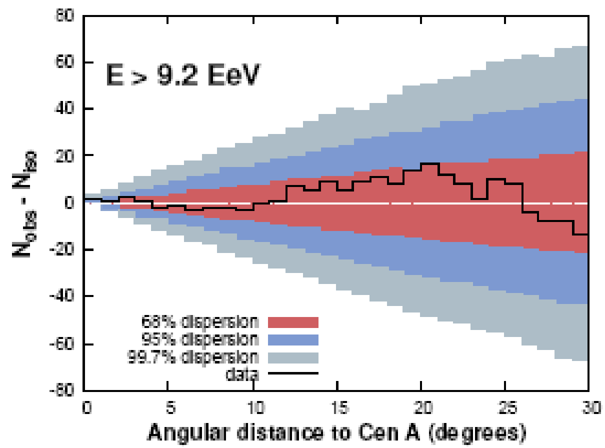
(3.2 expected from isotropy)

Excess around Cen A due to heavy nuclei?

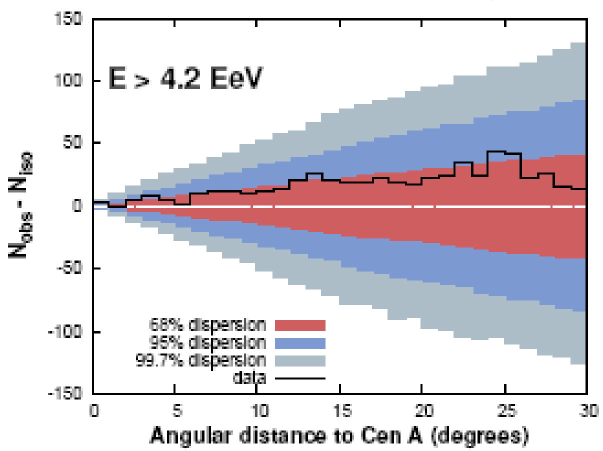
Anisotropies due to heavy primaries for $E>E_{th}$ should be present also for $E>E_{th}/Z$ due to the protons accelerated in the same source

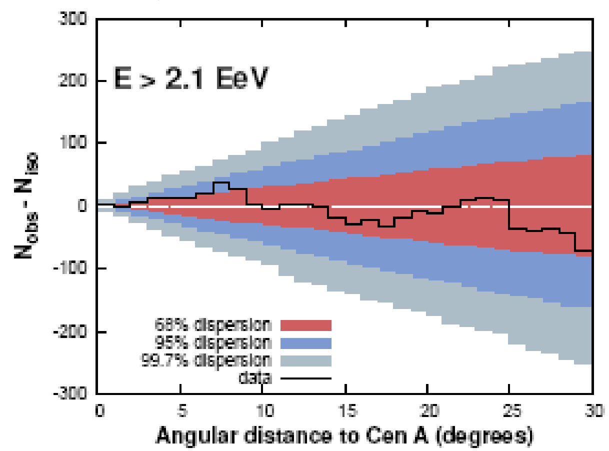
For E_{th}=55 EeV:

$E > E_{th}/Z$,
forZ=6, 13, 26



No indication of anisotropy at lower energies around Cen A

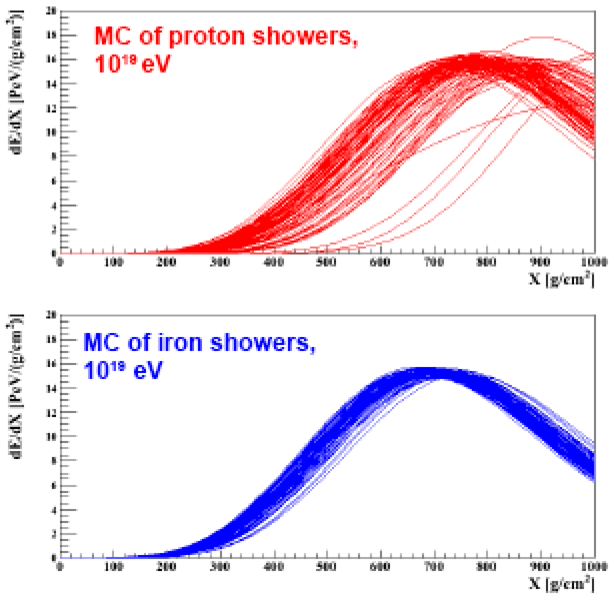


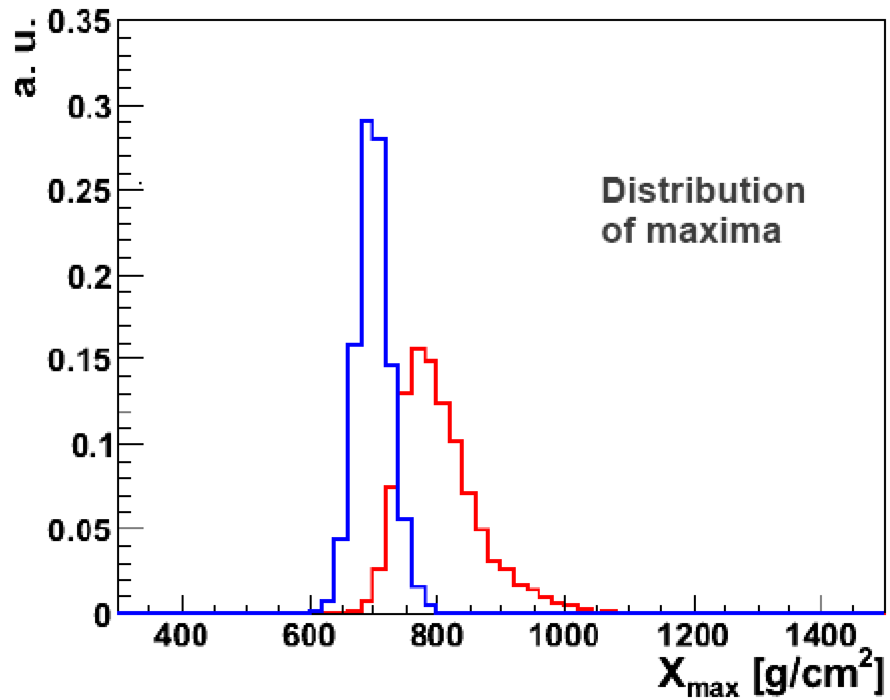


Composition

X_{max} and mass of the primary

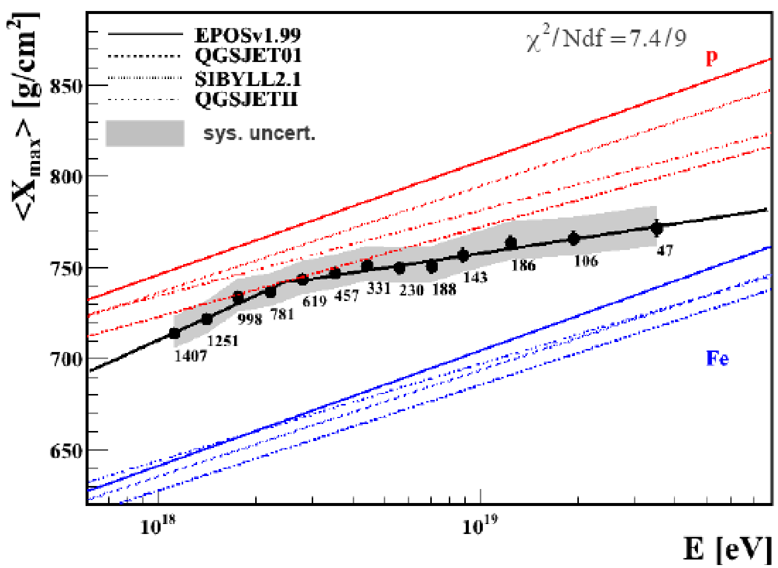
X_{max} reflects properties of the first interaction through X1

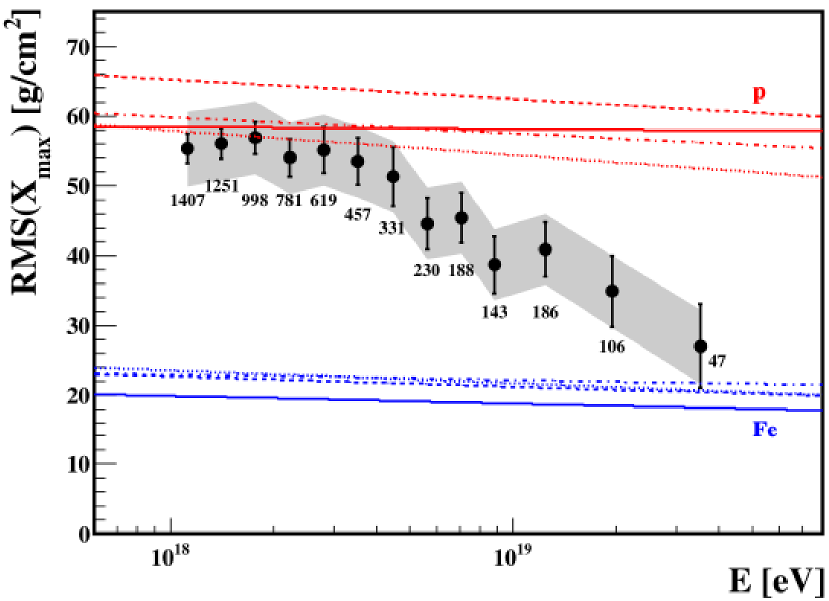




Distributions for heavy primaries are narrower and shallower
Light primaries, like protons, have a characteristic tail of deep X_{max}

X_{max} vs energy



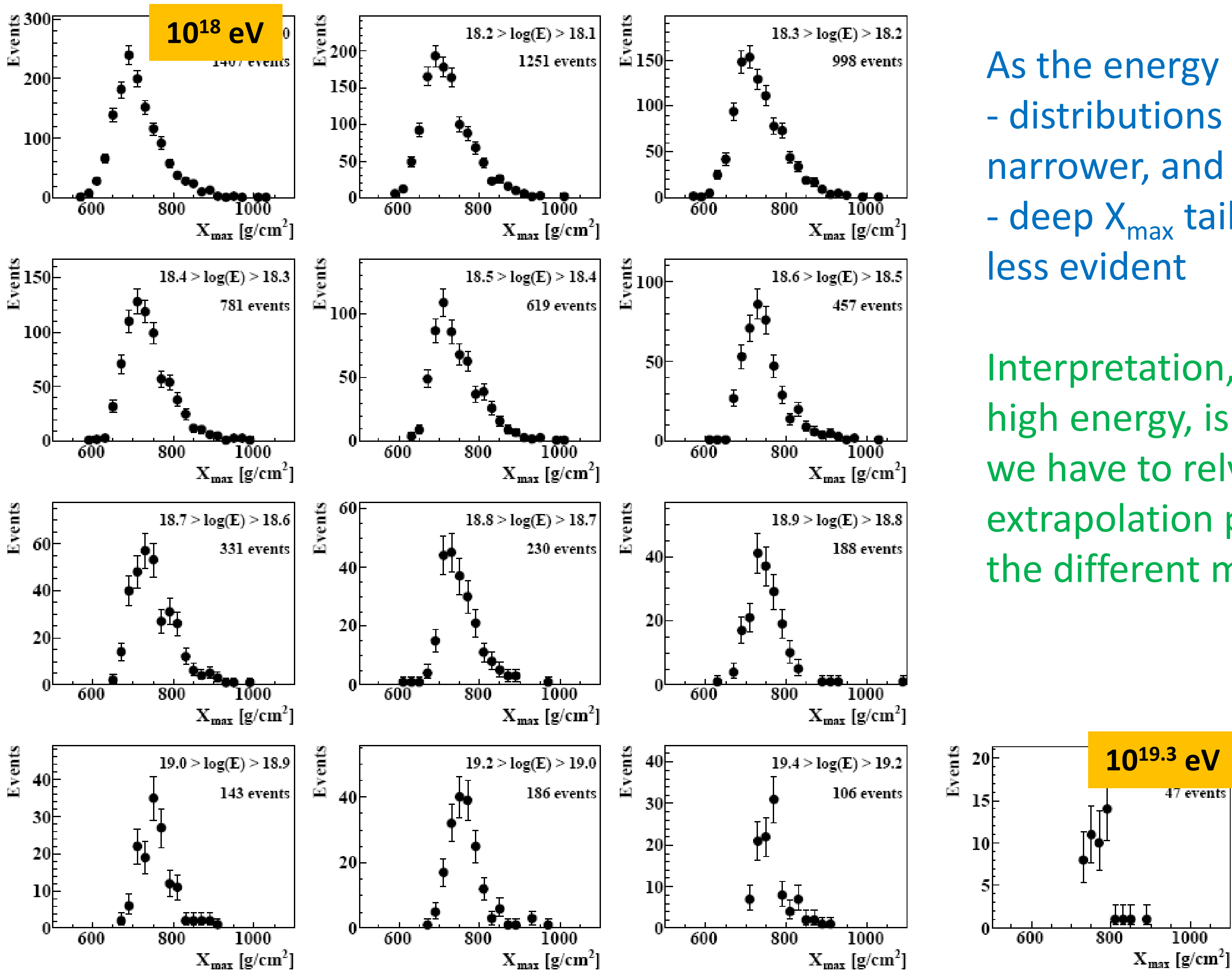


At low energy: significant fraction of protons
At high energy: heavy-like composition

→ Composition gets heavier with increasing energy?

Change of available model predictions would change interpretation

X_{max} distributions

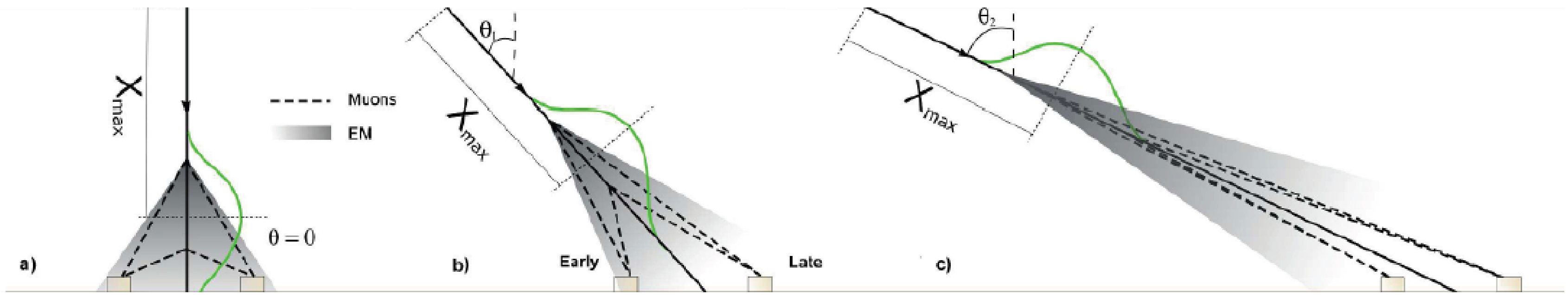


As the energy increases:

- distributions become narrower, and
- deep X_{max} tail becomes less evident

Interpretation, especially at high energy, is difficult since we have to rely on the extrapolation provided by the different models

Asymmetry of SD signal risetime

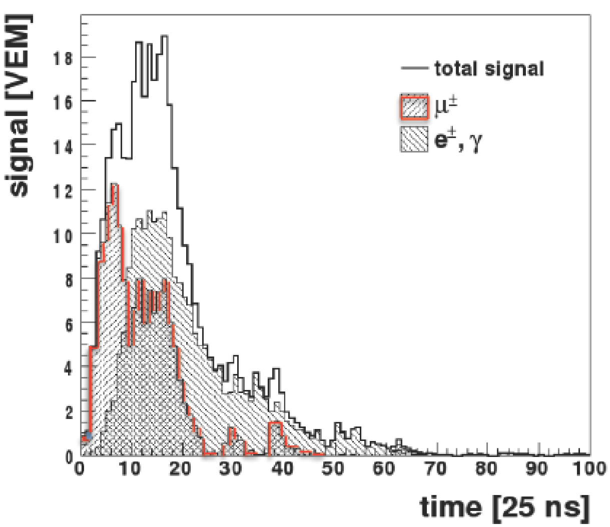


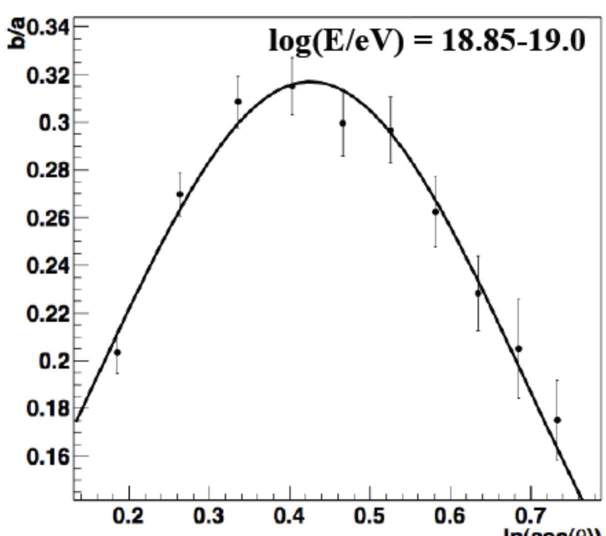
asymmetry

Risetime ($t_{1/2}$) = time needed to go from 10% to 50% of total signal

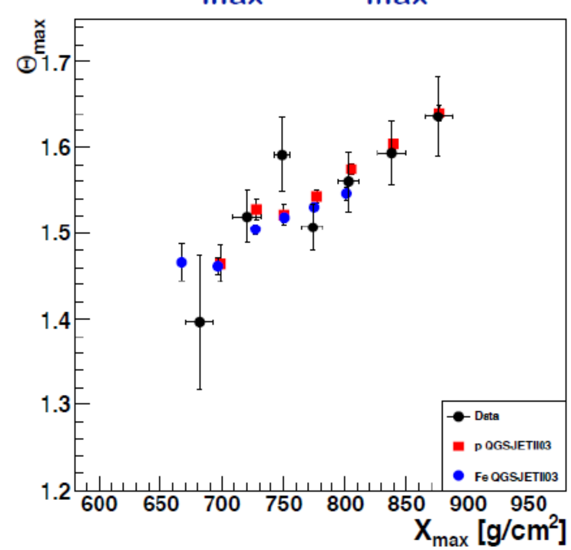
$$< t_{1/2} / r > = a + b \cos \varsigma$$

The early-late asymmetry (b/a) as a function of the zenith angle has a maximum Θ_{max} which is correlated with Xmax

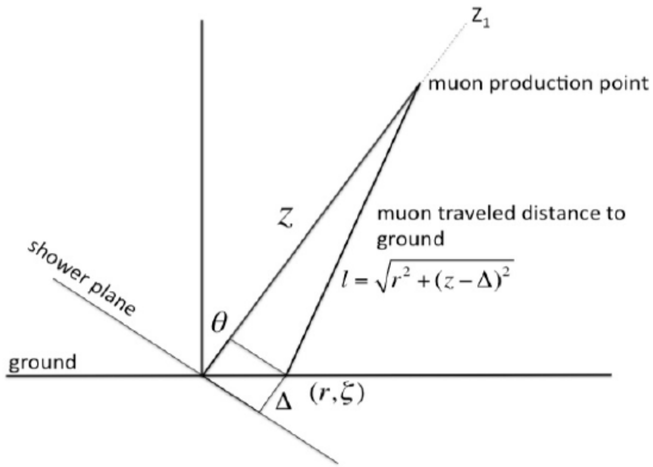




Θ_{max} vs X_{max}



Muon production depth

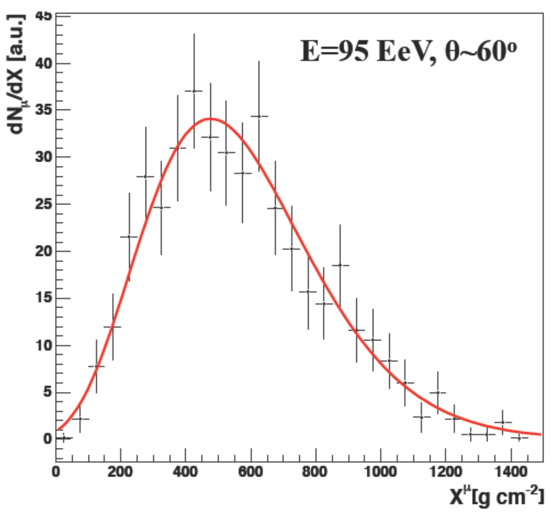


Muon production distance, z

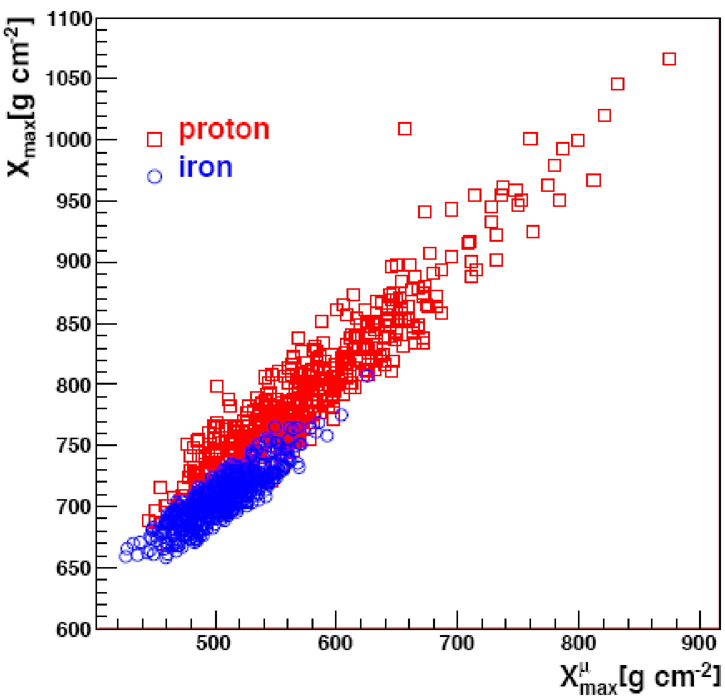
$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$

t_g is the time difference between arrival of muon and that of shower plane

Muon production depth provides information on longitudinal profile of hadronic component of the shower



X^{μ}_{max} vs X_{max}



Comparison of methods

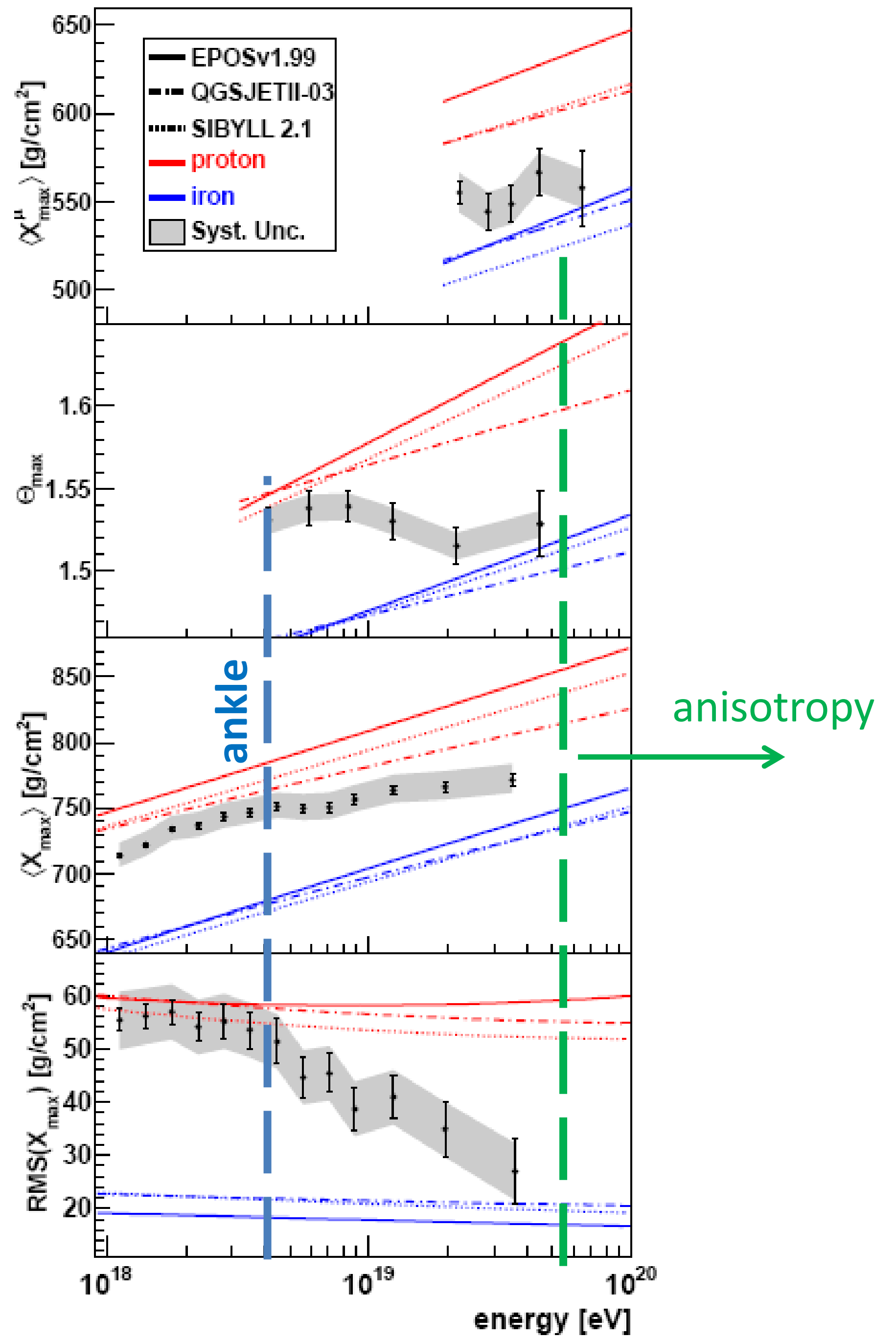
Muon production depth from timing differences in the Surface Detector $\rightarrow X^{\mu}_{max}$

Azimuthal asymmetry of signal risetime in the Surface Detector $\rightarrow \Theta_{max}$

X_{max} from Fluorescence Detector

$RMS(X_{max})$

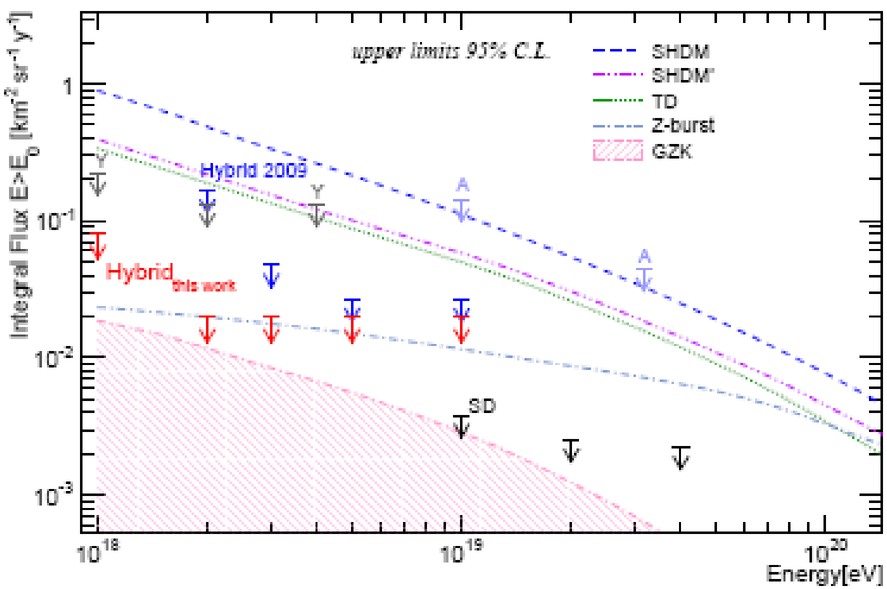
Composition gets heavier with increasing energy

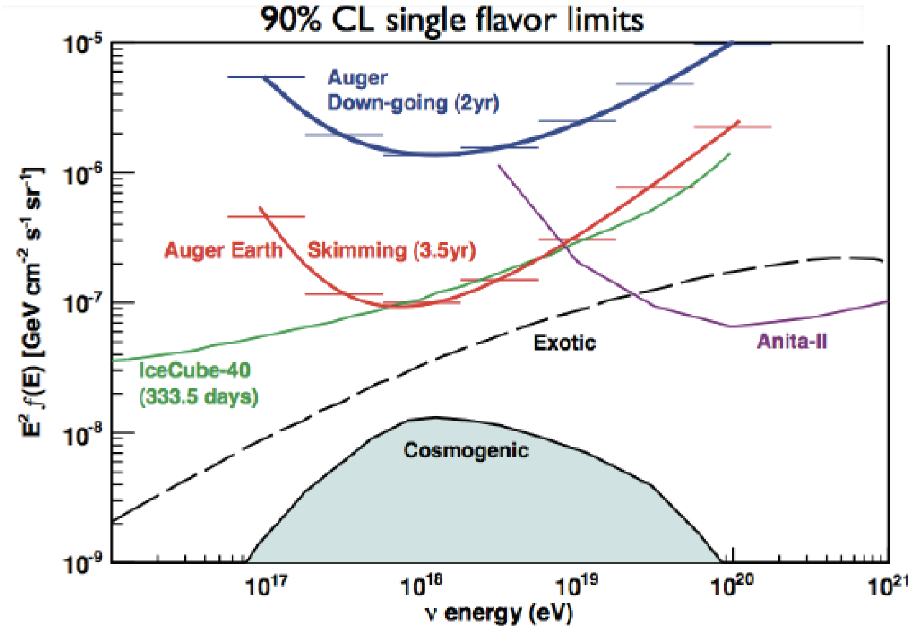


Photons and neutrinos

Showers from photon primaries
develop deeper (larger X_{max})
look young (larger risetime)

Showers from neutrino primaries
Can be 'horizontal' AND 'young'



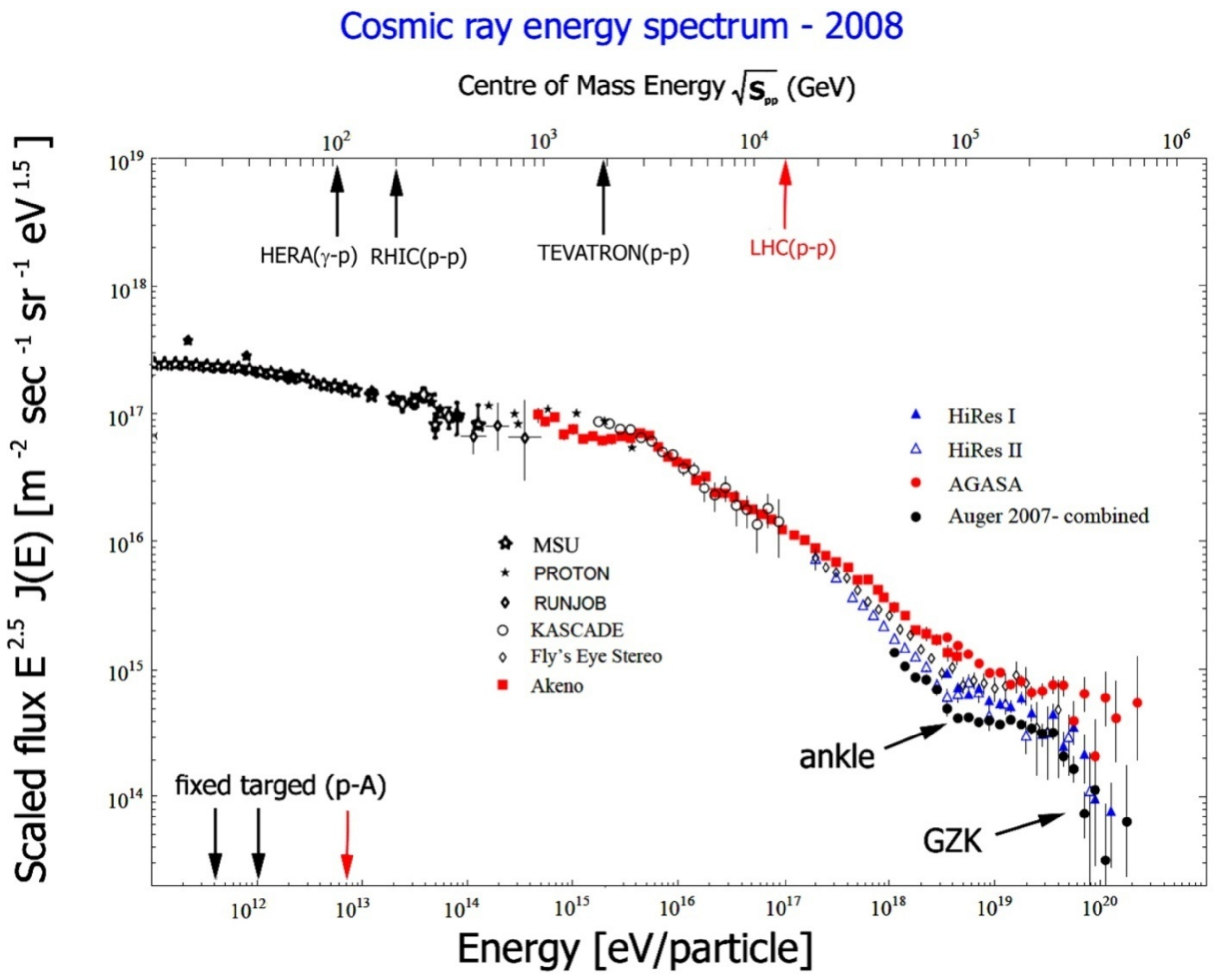


Exotic models disfavoured down to 1 EeV - CR composition looks truly baryonic

Cosmogenic photons and neutrinos within reach in next few years
Observation of GZK photons and neutrinos will verify the GZK effect

Hadronic interactions

Cosmic ray and accelerator energies



In modelling UHE showers, one needs to extrapolate properties of nuclear interactions from lower energies

Can do particle physics with cosmic rays

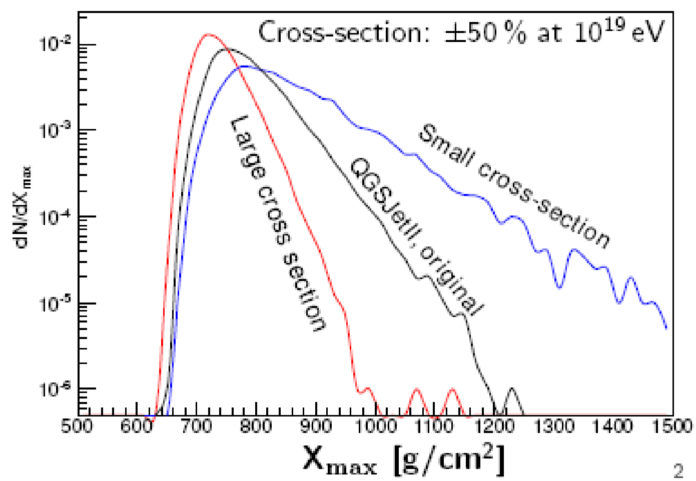
Proton-air cross section

Depth of first interaction directly linked to p-air x-section

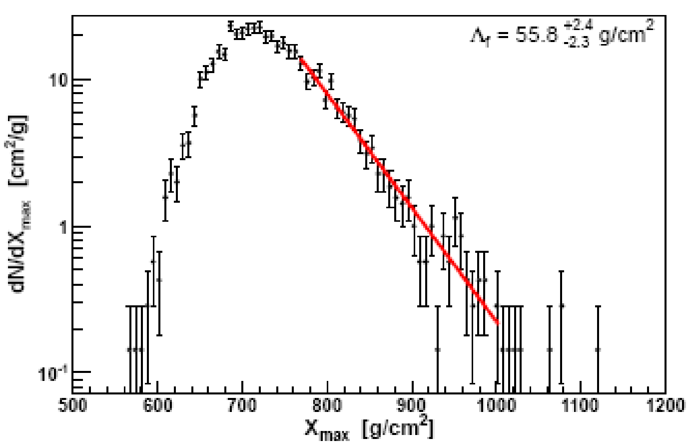
$$\frac{\mathrm{d}p}{\mathrm{d}X_1} = \frac{1}{\lambda_{\text{int}}}\,\mathrm{e}^{-X_1/\lambda_{\text{int}}}$$

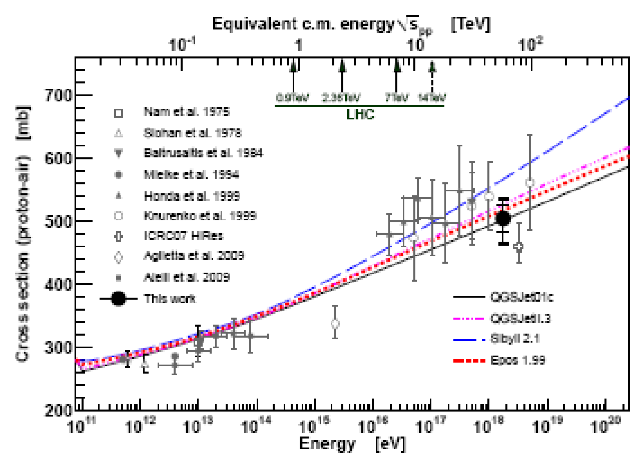
$$\mathrm{RMS}(X_1) = \lambda_{\text{int}}$$

$$\sigma_{\text{int}} = \frac{<m_{\text{air}}>}{\lambda_{\text{int}}}$$



Select deeply penetrating showers to enhance proton fraction





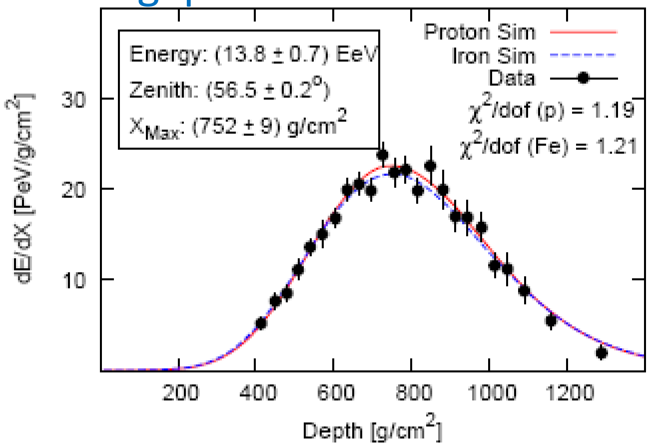
$$\sqrt{s_{\text{pp}}} = [57 \pm 6]\ \text{TeV}$$

$$\sigma_{\text{p-air}} = \left[505 \pm 22_{\text{stat}}\ (^{+28}_{-36})_{\text{sys}}\right]\ \text{mb}$$

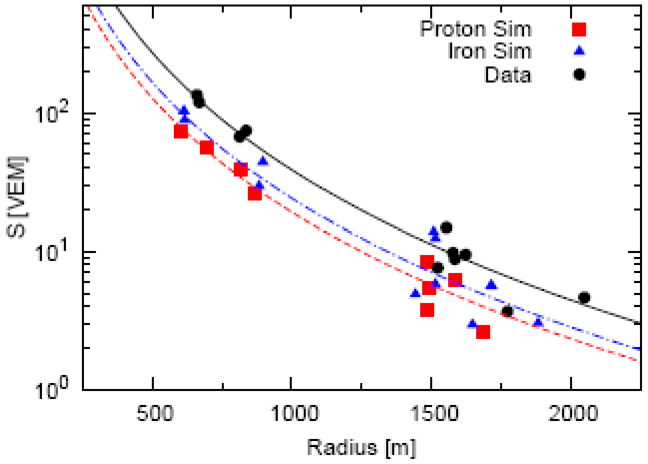
Test of hadronic interaction models

The existing models of HE interactions cannot consistently describe the data

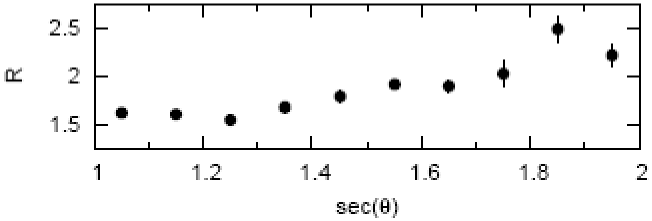
Measured event with simulated FD long. profile



The same event with simulated SD signal



Ratio S(data)/S(sim)



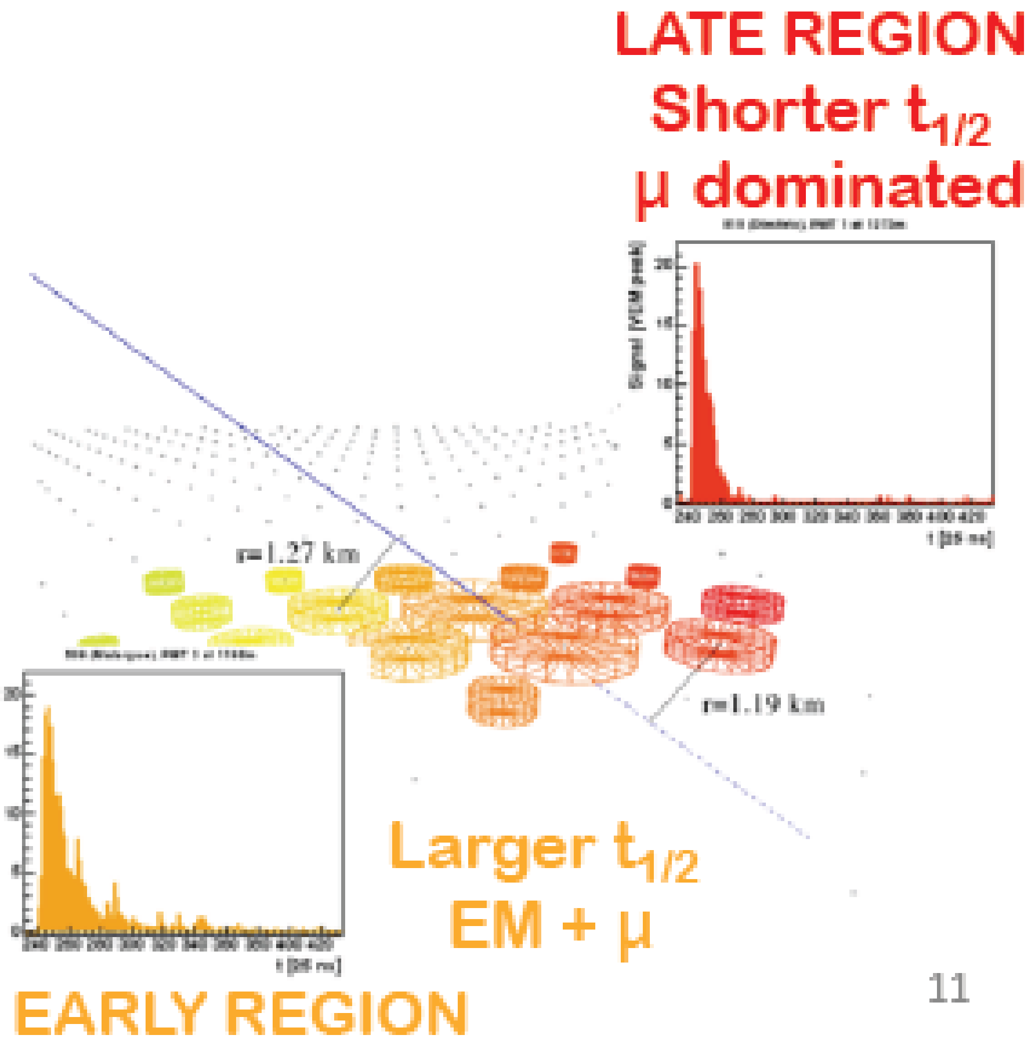
Models underestimate N_μ

Summary

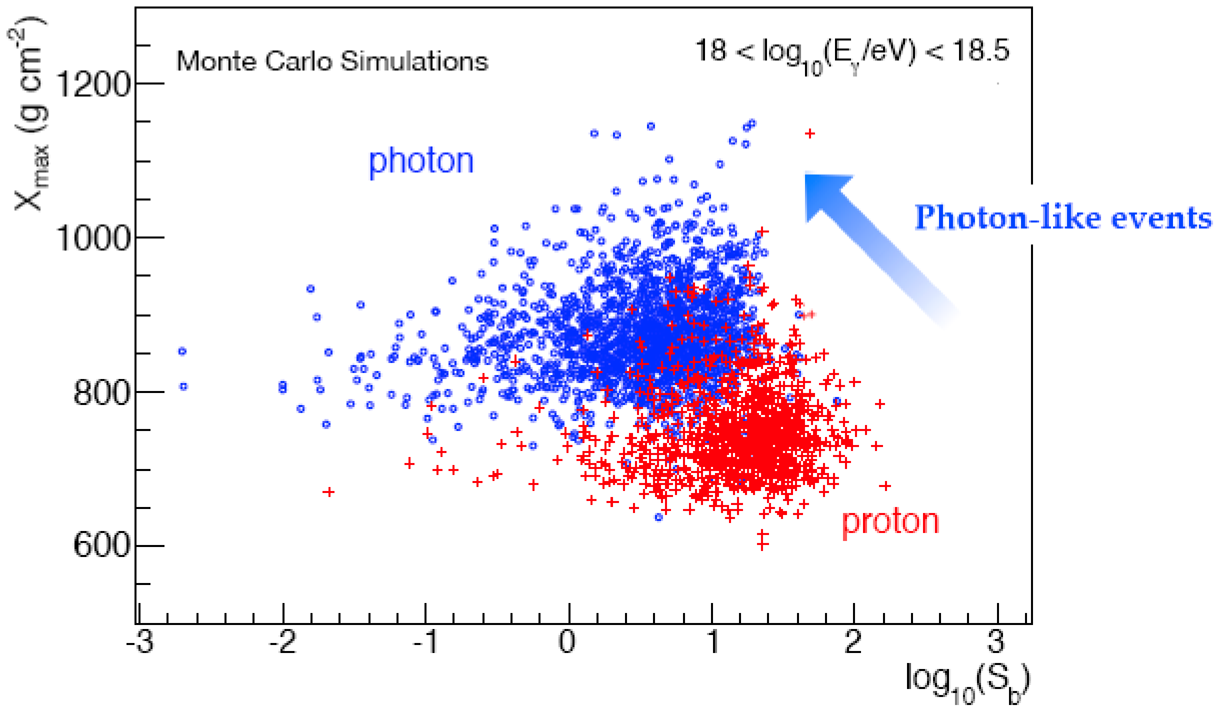
- Pierre Auger Observatory accumulates data
  superior data quality due to hybrid detection technique
- Energy spectrum of UHECR determined – GZK suppression seen
- Anisotropy of UHECR arrival directions
- CR composition gets heavier with increasing energy
- Limits on photons and neutrinos – exotic models constrained
- Measurement of p-air cross section at 57 TeV c.m. Energy
- Hadronic interaction models underestimate muon number by ~25-100%

Backup slides

Azimuthal asymmetry of signal risetime

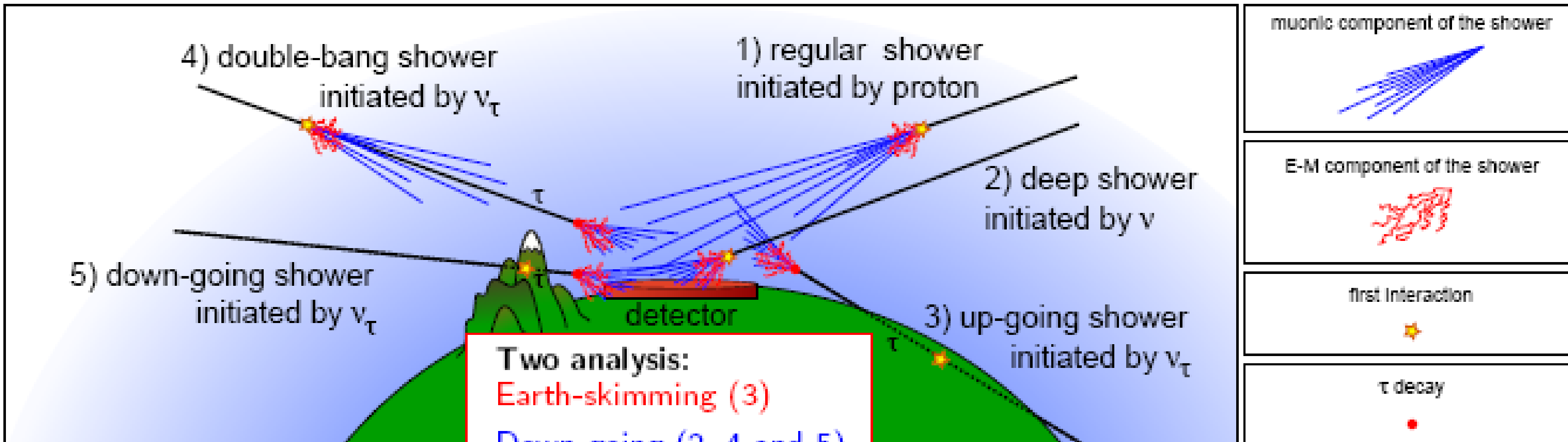


Identification of photon showers



$$S_b = \sum_i S_i \left(\frac{R_i}{1000}\right)^4$$

Identification of neutrino showers

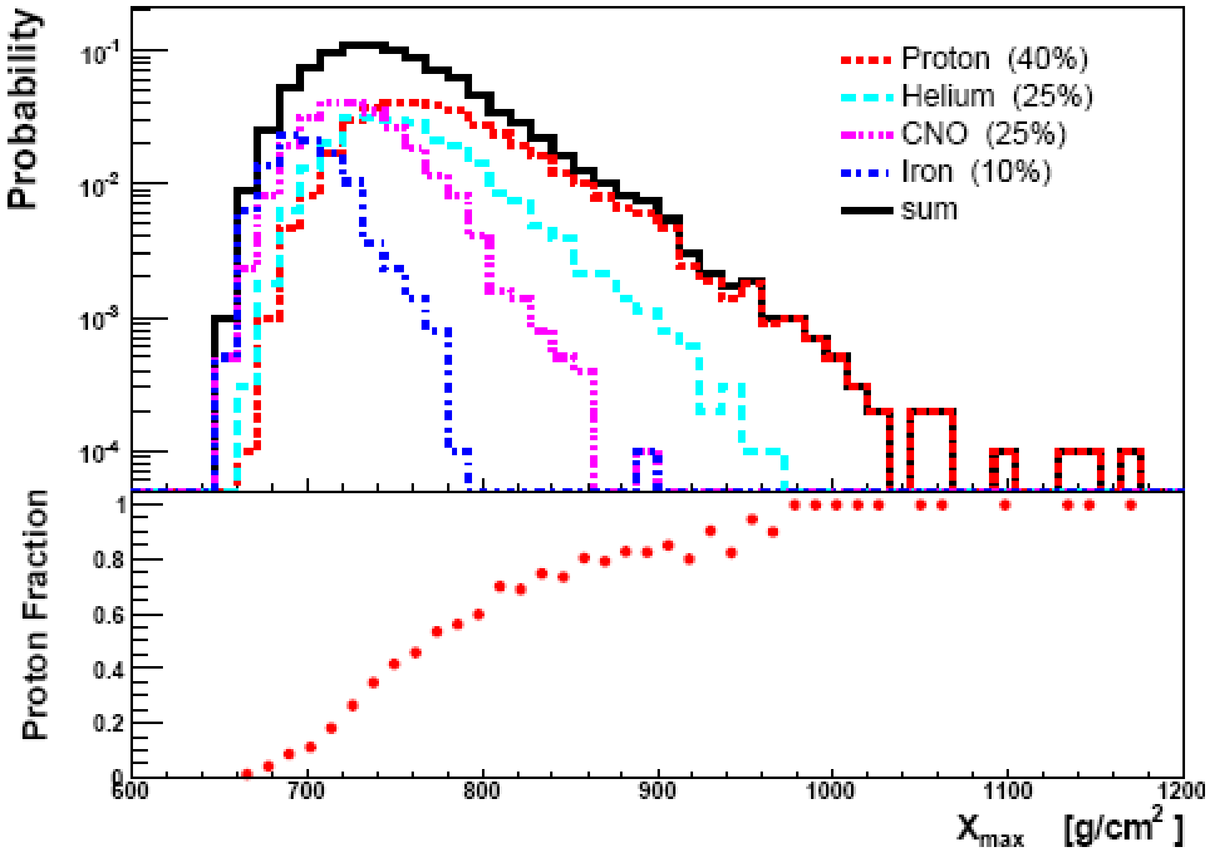


Two analysis:

Earth-skimming (3)

Down-going (2, 4 and 5)

Tail of X_{max} distribution



Select deeply penetrating showers to enhance proton fraction

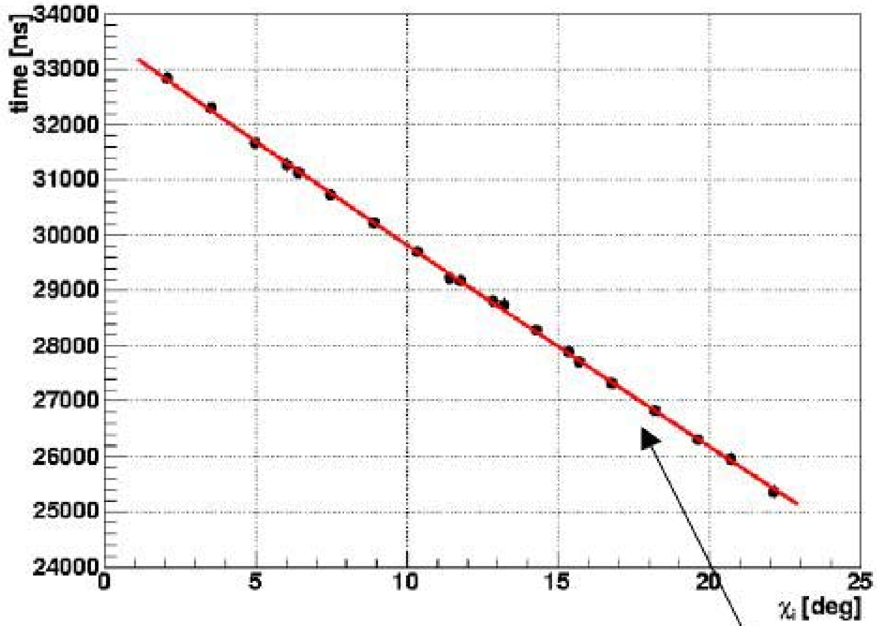
$\Rightarrow$ Tail of X_{max}–Distribution

Ellsworth et al. PRD 1982
Baltrusaitis et al. PRL 1984

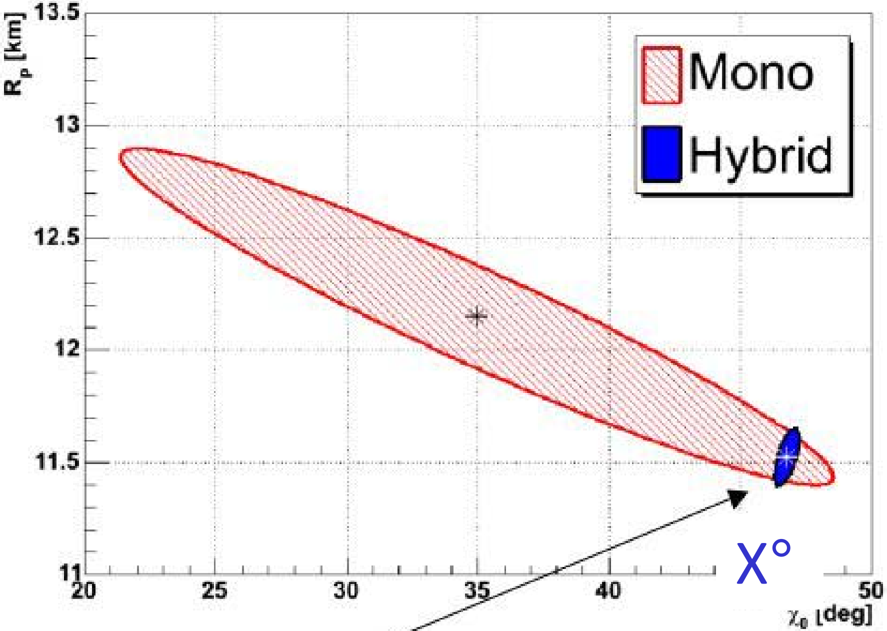
$$dN/dX_{max} \propto \exp(-X_{max}/\Lambda_\eta)$$

Hybrid vs Monocular

Time, t



R_p km



$\approx$ line but

3 free parameters

T_0 from tank!

$$t(\chi) = T_0 + \frac{R_p}{c} \tan\left[\frac{(\chi_0 - \chi)}{2}\right]$$